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# HIGH TEMPERATURE LUBRICANT SCREENING TESTS

by

L. A. Peacock and W. L. Rhoads

SKF INDUSTRIES, INC.

RESEARCH LABORATORY

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS3-11171
William R. Loomis, Project Manager

# NOTICE



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# FINAL REPORT

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King of Prussia, Pa.

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September 26, 1969

CONTRACT NAS3-11171

NASA Lewis Research Center
Cleveland, Ohio
William R. Loomis, Project Manager
Fluid System Components Division

# FOREWORD

The research described herein, which was conducted by the SKF Industries, Inc. Research Laboratory, was performed under NASA Contract NAS3-11171. The work was completed under the management of the NASA Project Manager, Mr. William R. Loomis, Fluid System Components Division, NASA Lewis Research Center.

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## ABSTRACT

Eight candidate aerospace lubricants have been evaluated for lubricating ability and stability at 600°F (589°K). A series of inerted screening tests were conducted using 25-mm bore angular contact ball bearings operated at 43,000 rpm (4500 rad/sec.) to simulate advanced aircraft applications.

The best of the eight lubricants tested, ranked by ability to prevent lubrication distress, surface damage, and lubrication related failures of the bearings proved to be a super refined naphthenic mineral oil base blended with 10% high molecular weight paraffinic resin. The next two best lubricants were a perfluorinated polyether containing a corrosion inhibitor and a modified fluorosilicone fluid. The third best candidate fluids were a synthetic hydrocarbon base blended with 10% high molecular weight paraffinic resin, and a modified polyphenyl ehter. The poorest of the lubricant candidates tested were a highly hindered ester formulation, a super refined mineral oil and a synthetic hydrocarbon.

Film thickness measurements conducted with all fluids, show that boundary lubrication properties play an important role in determining performance in high temperature bearing operation.

# FINAL REPORT OF NASA CONTRACT NAS3-11171

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by: L. A. Peacock and W. L. Rhoads

SKF Industries, Inc.

## SUMMARY

This is the Final Summary Report submitted in fulfillment of NASA Contract No. NAS3-11171 entitled "High Temperature Lubricant Screening Tests". It encompasses research conducted from June 27, 1968 through August 26, 1969 and previously reported in Monthly Progress Reports Numbers 1 through 13.

In this program, eight candidate lubricants for use in advanced high speed aircraft were evaluated in a series of screening tests using 25-mm bore angular-contact ball bearings. The following lubricants were evaluated: Mobil XRM-109F synthetic paraffinic hydrocarbon; Monsanto MCS-2931 modified polyphenyl ether; Humble FN-3158 super-refined mineral oil; Dow Corning XF-1-0301 modified fluorosilicone; Esso AL07873 highly hindered ester; DuPont Krytox 143 AB perfluoro alkyl polyether; and two of the above lubricants blended with Kendall Special Heavy Resin 0839 high molecular weight resin, Humble FN-3158 plus 10% Kendall Resin and Mobil XRM-109F plus 10% Kendall Resin.. Three tests were run under simulated jet engine conditions with each lubricant with film thickness measurements conducted during one of these tests to determine the dimensionless film parameter $h/\sigma$ (ratio of average film thickness, h, to bearing composite surface roughness, $\sigma$) which is a measure of the lubricating effectiveness under elastohydrodynamic conditions.

The screening tests were conducted on an SKF Industries, Inc. owned high-speed, high-temperature test machine which tests two 7205 size (25-mm bore) angular-contact ball bearings simultaneously. Test conditions for all screening tests were:

a time-up life of 100 hours corresponding to 258 million inner-ring revolutions, a thrust load of 300 lbs., (1334 Newton) corresponding to an AFBMA rated life of $L_{10}$ = 1270 mill.revs. and maximum Hertzian contact stresses of 215,000 psi (1.48 X $10^9 N/m^2$) and 217,000 psi (1.50 X $10^9 N/m^2$) on the inner and outer bearing rings, respectively, 43,000 rpm (4500 rad/sec.) inner-ring speed, and 600°F (589°K) bearing temperature (measured at the outer ring), and 150 cc/min. nominal lubricant flow rate to each bearing. The test rig and lubricant reservior were blanketed with nitrogen gas for inerting. Periodic oil samples were taken for chemical analysis. Rig oxygen content measurements are also taken.

The film measuring tests were conducted in the same manner as screening tests with the exception that a specially modified and instrumented test rig was used and the tests had a time-up life of 50 hours. New CVM M-50 tool steel bearings (SKF 7205 VAP or 7205 VAP-3 as specified) were used in each of the tests.

The results of all testing completed on this program are summarized briefly in the table below.

SUMMARY OF TEST RESULTS

| PERFORMANCE | FLUID (S) | MEASURED $H/\sigma$ @ 600° F | TYPICAL BEARING CONDITION |
|---|---|---|---|
| EXCELLENT | 1. SUPER REFINED MINERAL OIL PLUS 10% HIGH MOLECULAR WEIGHT RESIN. | 3.6 - 4.0 | GOOD. |
| GOOD | 2. PERFLUORINATED POLYETHER. | 3-4 (INITIALLY)<br><1.8 (LONG-TERM) | MINOR GLAZING AND MICROPITTING. |
| | 3. MODIFIED FLUOROSILICONE. | <1.8 | |
| ACCEPTABLE | 4. SYNTHETIC HYDROCARBON PLUS 10% HIGH MOLECULAR WEIGHT RESIN. | <1.8 | MODERATE GLAZING AND MICROPITTING. |
| | 5. MODIFIED POLYPHENYL ETHER. | <1.8 | |
| UNACCEPTABLE | 6. SUPER REFINED MINERAL OIL WITHOUT HIGH MOLECULAR WEIGHT RESIN. | 2.6-3.6 (INITIALLY)<br><1.8 (LONG-TERM) | |
| | 7. SYNTHETIC HYDROCARBON WITHOUT HIGH MOLECULAR WEIGHT RESIN. | 3.5-4.0 | HEAVY GLAZING AND PITTING. |
| | 8. HIGHLY HINDERED ESTER. | <1.8 | |

While this program was aimed primarily at determining suitability of the lubricants evaluated for use in full-scale engine mainshaft size bearing tests, the results are of immediate value for small bearings running at extreme conditions. Therefore, the following rating applies to the usefulness of the fluids in large engine mainshaft bearings as well as in small, auxiliary drive bearings. Humble FN-3158 plus 10% Kendall Resin proved to be the best of the lubricants tested and is rated as an excellent candidate for further full scale testing. Results obtained with this fluid are comparable to results obtained with the best fluid found from previous research, Mobil XRM-177F. DuPont Krytox 143AB and Dow Corning XF-1-0301 are both rated as very good candidates. Mobil XRM-109F plus 10% Kendall Resin and Monsanto MCS-2931 are rated acceptable candidates. Esso AL07873. Humble FN-3158 and Mobil XRM-109F are rated unacceptable lubricant candidates on the basis of their performance in the present tests and are not recommended for further full-scale tests.

## INTRODUCTION

7205-size angular-contact ball bearings have been tested in the SKF Research Laboratory at high speeds and temperatures on a continuing basis beginning in 1962 with NASA Contract NAS3-492 and continuing on NASA Contract NAS3-7912.

Simplicity of rig operation and relatively low cost of the 25-mm bore bearings have shown this approach to be a most economical means of evaluating bearing materials and lubricants for advanced aircraft applications. Tests of this type are considerably more economical than full-scale tests of 125-mm bore jet engine mainshaft bearings which have been conducted in the Laboratory under NASA Contract NAS3-6267.

It was the purpose of the present program to determine lubricating ability and stability of eight high-temperature lubricant candidates for use in high speed aircraft. Results of testing fluids in existing rigs using optimized 25-mm bore bearings will then be used in guiding future full-scale bearing and seal assembly studies.

## TEST RIGS

Two high-speed, high-temperature bearing test machines, developed and owned by SKF Industries, Inc., and modified as described below were used for all testing conducted on this contract. One of these rigs, fitted with a 43,000 rpm (4500rad/sec) constant speed drive, was used to conduct the lubricant screening tests. The second rig, modified for film measuring purposes as described in (1) was fitted with a variable speed drive and was used to conduct the film measuring tests reported herein.

A layout sketch of the basic test rig is shown in Enclosure 1 with its design and operation having been described in detail in (2). Essentially, each test rig tests two 7205 angular-contact ball bearings mounted on the same shaft and thrust loaded against each other by a dead-weight and lever system. Screw pumps machined in the shaft between the two test bearings circulate the test lubricant from a 2000 cc sump through the bearings and back to the sump through sight-flow tubes used as a visual check on the lubricant flow through the bearings. Nitrogen gas is supplied as an inert blanket over the oil in the sump and to both ends of the test bearing housing. Lubricant is replenished periodically to the sump as it is lost by slight leakage through the seals and by evaporation. Two 30 inch (.762m) standpipes, located in the nitrogen venting system, act as condensers to reclaim most of the oil that would normally be lost through evaporation.

Modifications to the test rigs entailed: 1. replacing the standard labyrinth seals with circumferential rubbing shaft seals (Clevite B104014) internally pressurized with nitrogen as shown in Enclosure 2. The purpose of this modification was to cut down test lubricant loss through leakage and reduce the percent oxygen present in the test chamber atmosphere. Comparison of oil makeup rates shows that this modification cut the leakage rate by 50% over the labyrinth seal mode of operation while oxygen contents were reduced from 0.9 - 1.0% to $<$0.05%.

2. The insertion of thermocouples into the rig inboard (before the bearing) drain lines to measure the temperature of the lubricant into the test bearings. Provisions already existed to measure lubricant temperature out of the test bearings.

3. The incorporation of two (per rig) larger diameter sight glasses plus appropriate valving and piping to set the lubricant flow rate to each bearing at 150 cc/min nominal by opening or closing by-pass valves in the rig and to measure flow periodically and reset if necessary. Lubricant flow is measured by timing the interval required for the lubricant to fill the sight glass to a predetermined level corresponding to an oil volume of 240 cc or approximately 12% of the total lubricant in the system.

Knowing both the flow rate and the temperature increase of the lubricant from 2, it is then possible to perform heat transfer calculations for the bearing lubricant system.

Small drain valves located on the bottom of the sight glasses are provided for the taking of oil samples while the rig is in operation.

4. The adaption of a radiation pyrometer to measure the inner-ring temperature of the load-end bearing through a line-of-sight viewing port incorporated into the rig loading plug is shown in Enclosure 3. Inner-ring temperature measurements were taken for the screening tests only.

Early in the program some difficulties were encountered with oil collecting in the sight tube which made the temperature readings unreliable. A number of modifications were employed, including gravity draining and sweeping the tube with nitrogen, in an attempt to rectify this. A calibration was then performed by comparing measurements of the outer ring temperature with thermocouple readings. This showed that the presence of the lubricant being used at that time (the modified polyphenyl ether) did not significantly affect the accuracy of the pyrometer readings. However, in a more recent program for another sponsor, it was noted that pyrometer measurements changed (decreased) by as much as 60°F (289°K) when all lubricant (an ester) was drained from the system. Since the draining of lubricant could have affected bearing temperature this does not necessarily indicate pyrometer readings are in error. However, in view of this and because many chemically (and optically) different fluids were used in this program the inner-ring temperature measurements should not be regarded as absolute since there is some possibility of inaccuracy.

Each rig is driven through a speed-increaser gearbox and quill coupling to the test shaft. The one rig used for screening tests is fitted with constant speed 60 horsepower (44,760W) AC induction motor drive and the rig instrumented for lubricant film measurements is fitted with a variable speed 50 horsepower (37,300W) DC motor drive. Each rig is located with its drive in an explosion-proof test cell. An overall view of one test rig in its test call is shown in Enclosure 4. Test bearing and oil temperatures are maintained by electrical cartridge heaters in the rig housing and sump walls, the heaters being controlled by time-proportioning on-off temperature controllers. Temperature fluctuations are evened out by the relatively massive steel sections in which the heaters are imbedded. At the high bearing thrust loads and speeds used, the test bearings themselves generate almost enough heat to maintain the rig temperature at 500°F to 600°F, (533°K to 589°K) so that fan cooling of the housing is employed to the degree necessary to maintain some heater input power for temperature control purposes. Automatic shut-down of the rig occurs if the oil pressure from either screw pump decreases below a preset limit or if a vibration-sensitive switch attached to the load lever arm detects an increase in rig vibration level. A shear pin in the drive coupling prevents excessive torque loading. During testing, the bearing outer-ring temperatures are monitored every 6 minutes by a central data collection system described in (2) which provides an audible alarm should either test bearing temperature vary from the prescribed temperature by more than a preset number of degrees (± 15°F ± 8.33°K ).

Lubricant film measurements are made using a system originated by SKF Industries, Research Laboratory and further developed under NASA contract NAS3-7912, which measures the elastohydrodynamic lubricant film thickness of operating 7205 bearings. The system is composed of instruments for an AC conductivity and a capacitance measuring technique which together, cover bearing operation in partial and full EHD lubrication regimes. The initial development of this system has been discussed in (1) and the system was successfully used to gather film thickness information reported in (3). A photograph of the current measuring system instrumentation is shown in Enclosure 5.

## TEST BEARINGS

CVM M50 tool steel bearings were used in all tests conducted on this program. The bearings used were of two similar designs: 7205 VAP and 7205 VAP-3 with 16 bearings of the former type being used to initiate the program and 24 bearings of the latter type being used, as soon as they became available, to carry the program through to completion. Enclosure 6 gives the design details for the 7205 VAP-3 bearings and the 7205 VAP design is shown in Enclosure 7.

The 7205 VAP inner and outer rings and the 7205 VAP-3 outer-rings are from the same heat of CVM M50 steel and were heat treated together. The 7205 VAP-3 inner rings are from a separate heat of CVM M50 steel. The 5/16 + .005" (7.9375 + .127mm) balls for the 7205 VAP bearings and the 6/16 + .010" (7.9375 + .254mm) balls for the 7205 VAP-3 bearings are each from separate heats of CVM M50 steel.

The analysis of each lot of steel obtained for test bearings was checked and found within the limits given in Enclosure 8. Steel samples from each heat treatment lot were checked metallurgically for proper structure and hardness as listed in Enclosure 8. Dimensional measurements before testing on all bearings used in this Task are given in Enclosure 9.

The cages used in all test bearings, except those used for film measurements, were made of Ml steel heat treated to a hardness of Rc 57 to 60 and electroplated with silver to a thickness of .001" to .002" (.025 to .050mm). This cage material and the design shown in Enclosure 10 for bearings having counter-bored inner rings are based on the results of previous studies (2, 4) indicating good performance under extreme lubrication conditions.

The cages used in the film measurement test bearings were similar in design to the standard Ml steel cages shown in Enclosure 10 but were made of a special non-metallic, high temperature polyimide material manufactured by DuPont de Nemours & Co., Inc., Wilmington, Delaware and designated as Vespel SP-1. The polyimide cage is used to prevent electrical ball-to-ball shorting of the measuring signal which would invalidate the probability analyses described in (1) which are used to convert measurement data to film parameters.

## TEST LUBRICANTS

Eight different candidate lubricants were obtained for use on this program. Prior to testing all lubricants were vacuum degassed to remove dissolved oxygen using the apparatus described in (5). In the degassing process lubricants are subjected to a pressure of $10^{-3}$ mm Mercury either for a 72 hour period at room temperature or at a temperature not exceeding 200°F (366°K) for a period of at least one hour for more viscous lubricants. Nitrogen is used as a cover gas. All eight lubricants are described individually below in the order of their testing with a listing of lubricant properties data being given in Appendix I.

### 1. Mobil XRM-109F - Synthetic Paraffinic Hydrocarbon

This fluid is a hydrocarbon material synthesized by the polymerization of a fairly pure mono-olefin so that it can be considered a single chemical species composed of molecules of a chain length distribution depending on the type, method and degree of polymerization. It has a reasonably good resistance to thermal degradation and is susceptible to additive improvement.

Mobil XRM-109F lubricant from lot 4 was used for the tests reported herein.

In an earlier research program (2), endurance tests of 7205 size tool steel bearings using XRM-109F lubricant resulted in a superficial pitting or "glazing" type of surface distress in the bearing raceways. In addition, a number of bearing smearing failures were obtained at relatively low lives. In a later program (3) lubricant film thickness measurements conducted on 7205 size bearings lubricated with XRM-109F (lot 2 and lot 3) under test conditions similar to the present program, showed a film parameter value, $h/\sigma$ of approximately 3 at 600°F (589°K). The fact that the bearings were also "glazed" and superficially pitted in these later tests was taken as an indication of the rather poor boundary lubricating quantities of XRM-109F lubricant. This fluid, without additives was therefore considered unacceptable for long term bearing operation at temperature in the 600°F (589°K) range, and was included in this program to serve as a baseline test for comparison with past results.

However, in former research programs, (6, 7) XRM-177F lubricant (XRM-109F containing a proprietary anti-wear additive), exhibited very good performance for long term bearing operation at 600°F (589°K) (no derating in bearing catalogue life required) and for shorter times at up to 750°F (672°K).

2. <u>Monsanto MCS-2931 - Improved MCS-293, Modified Polyphenyl Ether</u>

This is a formulated polyphenyl ether which possesses better wetting characteristics at high temperatures and thus should prove a more efficient heat transfer agent. It does not have as high a molecular weight or viscosity as some of the earlier polyphenyl ethers but does seem to be a more stable lubricant under a wide range of ambient conditions.

3. <u>Humble FN-3158 - Super-Refined Naphtenic Mineral Oil</u>

This is a natural mineral oil which has been selectively refined by the so-called super refining process to give a very pure hydrocarbon material with little or no aromatic or olefinic content. It is quite thermally stable and susceptible to additive enhancement.

4. <u>Humble FN-3158 plus 10% Kendall Resin - Super Refined Naphthenic Mineral Oil plus 10% High Molecular Weight Paraffinic Resin</u>

This is an examination of the capability of the Kendall Resin to act as an anti-wear additive in a naphthenic type oil.

The Kendall Special Resin 0839 is a very high molecular weight residual of a Pennsylvania crude oil which has been subjected to a rigid super refining process, the details of which are to some extent proprietary. In bench scale experiments it has shown properties of an additive to enhance the lubricating qualities of other hydrocarbon oils and in this project was used to test the possibility of replacing conventional synthetic anti-wear additives.

5. <u>Dow Corning XF-1-0301 - Modified Fluorosilicone</u>

Silicone oils in which all or part of the hydrogen has been substituted by fluorine have long been thought to hold considerable promise as lubricating fluids. Several of these are already being marketed by the Dow Chemical Company and have shown good high temperature lubricating properties. The material used here is one of the latest products to come from their research and development in attempts to achieve further improvements.

6. Mobil XRM-109F plus 10% Kendall Resin - Synthetic Paraffinic Hydrocarbon plus 10% High Molecular Weight Paraffinic Resin.

This formulation consists of 90% of the aforementioned Mobil Oil Company XRM-109F plus 10% of super-refined Kendall Heavy Resin (6600 cs).

7. Esso AL07873 - Highly Hindered Ester

This fluid is a very highly hindered nonconventional ester which is blended with an inhibitor. This experimental formulation complies with the physical properties required for 5 cs aviation lubricants, which most highly hindered esters fail to meet. Although AL07873 probably approaches the optimization of ester oxidative performance, further improvement in deposit forming tendencies and load carrying ability could still be incorporated.

8. DuPont Krytox 143 AB - Perfluoro Alkyl Polyether Containing a Proprietary Additive

This fluid is a perfluorinated polyether having excellent thermal and oxidative stability and high temperature viscosity (2.1 cs at 500°F (533°K). A corrosion inhibitor has been added to limit corrosive effects on martensitic steels at temperatures above 550°F (561°K) which in the past has somewhat limited this fluid's usefulness by dictating the use of special nickel alloys for all wetted parts, other than bearings, for extended test runs. This fluid, less additive, has shown promising performance in simulated jet-engine mainshaft bearing tests at temperatures up to 700°F (644°K) (8). In a previous program (3), lubricant film thickness measurements were made using this fluid, less additive, in 7205 bearing tests at temperatures up to 700°F (644°K). In those tests, film parameter values of $h/\sigma$ (ratio of average film thickness, h, to bearing composite surface roughness, $\sigma$ ) = 4 were obtained for short term operation at 600°F (589°K).

## TEST PROCEDURE

### a. Lubricant Screening Tests

The standard procedure used for conducting the lubricant screening tests reported here is as follows:

1. The rig is assembled with the test bearings and an initial charge of vacuum degassed test lubricant in the sump.

The load is applied, all valves in the oil lines are closed, except the inboard bearing drain valves which are set at one turn open (the specified setting for 43,000 rpm (4500 rad/sec) and the nitrogen blanket gas flow is started over the oil in the sump.

2. The rig is preheated for about an hour with both the housing and sump heater controllers set at 300°F (422°K).

3. The rig is started by first increasing the nitrogen flow to the sump wide open and closing the sump vents to prime the screw pumps on the test shaft. When oil starts to flow out the drive-end labyrinth seal with the shaft rotated slowly by hand, the sight-glass outboard drain valves and sump vent lines are open simultaneously with starting the drive motor. In the screening tests, a 60 hp (44,760W) AC drive motot is used which results in a high-speed startup whereby the test bearings achieve a top speed of 43,000 rpm (4500 rad/sec) in approximately 3.5 seconds.

Then the nitrogen flow to the sump is reset to the preheat level, the nitrogen flow lines to the housing cavities are opened, the sump heaters are turned off and the housing heater controller is set to the test temperature.

4. The lubricant flow rate to each test bearing is established at 150 cc/min. (nominal), which is then rechecked once every 10 hours and reset if necessary.

5. The test bearing outer-ring temperatures are monitored every 6 minutes by the central data collection system described in (2). The inner-ring temperature of the load end bearing is measured with a radiation pyrometer generally once an hour. As the test temperature is approached either one or two cooling fans are turned on. The position and number of fans is determined by "cut-and-try" during the first hour of running. The final fan placement is selected to provide a sump temperature cooler than the bearings and to leave some power input to the housing heaters for bearing temperature control.

Test lubricant temperature into and out of both bearings are also monitored every 6 minutes. Lubricant samples are taken after 2, 10, 50, and 100 hours of running and are later chemically tested to determine if changes have occurred in viscosity, acid number and dirt content. Also, any solid lubricant decomposition products found in the rig upon disassembly are preserved for analysis.

Oxygen content of the bearing cavity is measured once every 10 hours to insure that oxygen concentration does not exceed a level of 0.5% maximum.

6. Test lubricant lost by evaporation and seal leakage is replenished to the sump during each test at a rate of about 50 cc per hour for 600°F (589°K) tests. Automatic shut down of the rig occurs if the oil pressure from either screw pump decreases below a preset limit of 30% of the normal oil pressure or if a vibration-sensitive switch fastened to the load lever arm detects an abrupt increase in rig vibration level. The rig is disassembled for inspection of the test bearings if manual rotation of the shaft with the bearings under load indicates any unusual roughness in the bearings. Testing of both bearings is terminated when a time-up life of 100 hours is reached or when either test bearing fails.

b. Film Measuring Tests

The procedure used for all film measuring tests reported here is as follows unless otherwise indicated:

1. Prior to running a test series, the surface roughness values of the test bearing rolling elements (rings and balls) are measured and the composite rms surface roughness value of the bearing, $\sigma$, is computed as shown in Appendix II of (3). Groove profile traces of some bearings may also be made prior to testing as needed.

2. The rig is assembled and checked to insure that all electrical connections to the measuring system are properly made. The instruments comprising the measuring system are allowed to warm-up for approximately one half hour before making the necessary pre-test settings as specified in (1). The rig is started in accordance with step No's 1 through 4

of the test procedure described above for screening tests with the exception that slow speed start-up is used. That is, the rig is driven by a 50 hp (37,000W) variable speed DC motor which permits the test rig to come first to a speed of 20,000 rpm (2,093 rad/sec) which is then gradually increased to 43,000 rpm (4500 rad/sec) over a period of approximately 20 seconds. 20,000 rpm (2,093 rad/sec) is the minimum start-up speed required for the screw pump to prime. After reaching test speed, the rig is then run in accordance with step No's 5 and 6 of the above reference procedure with the exceptions that inner-ring temperature measurements and periodic lubricant sampling are not required and a time-up life of 50 hours is used.

3. After reaching the prescribed test speed, lubricant film measurements are taken continuously during the initial hour of operation while bearing temperature is being increased from 300°F (422°K) to the 600°F (589°K) test temperature, and then approximately once every ten hours after that at steady-state temperature conditions, until a 50 hour time-up life is reached, or failure occurs. Test bearing outer-ring temperature is measured using a thermocouple and precision potentiometer when film measurements are periodically being made and by the standard IBM monitoring system for standard operation between film measuring intervals. In the tests reported herein, lubricant film thickness measurements were sometimes made more often than at ten hour intervals and in some instances were taken at one hour intervals to check for transient changes in the film condition.

4. The rig is disassembled and the test bearings are first visually examined and then later checked under a 7 to 30X microscope. The post-test surface roughness of the bearing rolling elements (rings and balls) are measured. Profile traces of the bearing rings are also made as required. In instances where the bearings show severe surface distress, it is sometimes impossible to make meaningful roughness measurements or traces; however, a photographic record of the tested bearings is always kept.

5. The raw measurement data obtained from the tests are reduced to film parameters ($h/\sigma$ ratios or film thickness) which are plotted against time. The curves thus plotted are presented in Enclosures 12 through 19. Data reduction is accomplished through the use of "calibration" curves developed and presented in (1).

## TEST RESULTS

The results of testing eight candidate lubricants on this program are summarized briefly in Enclosure 11 and are described in greater detail in the text. A highly detailed description of all tested bearings is given in Appendix II. Chemical analysis data for acid number, dirt content, and viscosity for lubricant samples taken during one screening test with each lubricant are given in Appendix III. Bearing temperature (inner and outer ring) and oil temperature (in and out) data are given in Appendix IV. Power consumption figures are given in Appendix V. Plots of $h/\sigma$ vs. time for each of the lubricants tested are given in Enclosures 12 through 19. Photographs of one bearing from each test are given in Enclosures 20 through 41 and before and after groove profile traces for at least one bearing tested with each lubricant are given in Enclosures 42 through 49. Photographs of the wetted rig components after one test with each lubricant are given in Enclosures 50 through 55.

## DISCUSSION, GENERAL

Test results given in the previous section have been condensed in the table below. Lubricant candidates have been ranked primarily on the basis of overall condition of tested bearings, but also including measured film parameter values and chemical stability.

### Table

| RANKING | LUBRICANT | TEST SERIES NO. | NO BRGS REACHING TIME UP/NO BRGS TESTED | TYPICAL BEARING CONDITION | MEASURED $h/\sigma$ AT 600°F CONDUCTIVITY | MEASURED $h/\sigma$ AT 600°F CAPACITANCE | CHEMICAL ANALYSIS ($O_2$ CONTENT) NEVER EXCEEDED 0.01% |
|---|---|---|---|---|---|---|---|
| EXCELLENT | HUMBLE FN-3158 PLUS 10% KENDALL RESIN | 4 | 6/6 | VERY GOOD CONDITION; LIGHT DEBRIS DENTING. | 3.6-4.0 | 1.2-2.0 | GOOD STABILITY AFTER 100 HOURS. |
| GOOD | DU PONT KRYTOX 143AB WITH ADDITIVE | 8 | 2/2 | GOOD CONDITION; VERY LIGHT MICROPITTING. | 3.0-4.0(7.6 HRS) <1.8 (42.4 HRS) | 1.7-2.8 | 12% VISCOSITY INCREASE* AFTER 50 HOURS. |
| | DOW CORNING XF-1-0301 | 5 | 6/6 | MINOR GLAZING AND MICROPITTING. | <1.8 | - | 45% VISCOSITY INCREASE* AFTER 100 HOURS. |
| ACCEPTABLE | MOBIL XRM-109F PLUS 10% KENDALL RESIN | 6 | 6/6 | MODERATE TO HEAVY MICROPITTING WITH GENERALLY LIGHT GLAZING. | <1.8 | - | 18% VISCOSITY INCREASE* AFTER 100 HOURS. |
| | MONSANTO MCS-2931 | 2 | 2/6 | MODERATE TO HEAVY PITTING, MICROPITTING AND DEBRIS DENTING. | <1.8 | - | 22% VISCOSITY INCREASE* AFTER 100 HOURS. |
| UNACCEPTABLE | ESSO AL07873 | 7 | 0/6 | SPALLED BALLS; MODERATE TO HEAVY GLAZING. | <1.8 | - | GOOD STABILITY BUT OIL TURNED BLACK AFTER 100 HOURS. |
| | HUMBLE FN-3158 | 3 | 6/2 | EXTENSIVE PITTING. | 2.6-3.6(11.1 HRS) <1.8 (38.9 HRS) | - | GOOD STABILITY AFTER 71.7 HOURS. |
| | MOBIL XRM-109F | 1 | 6/2 | SEVERE GLAZING WITH PITTING AND MICRO-PITTING. | 3.5-4.0 | 1.8-2.7 | GOOD STABILITY (TEST RAN ONLY 14.3 HOURS). |

* MEASURED AT 100°F

Of all the lubricants tested, bearings run with Humble FN-3158 plus 10% Kendall Resin were judged to be in the best condition. The six bearings run with this fluid had practically no lubrication related surface distress even in the presence of light debris denting. These results compare very favorably with results of tests run using straight Humble FN-3158 lubricant which were characterized by heavy pitting of the test bearing inner and outer ring raceways. The dramatically improved performance of the blended version is attributed to the addition of 10% (by weight) Kendall Resin which apparently increases the viscosity in the Hertzian contacts even though it does not significantly increase the bulk oil viscosity. This is evidenced by measured $h/\sigma$ values of 3.6 to 4.0, at these test conditions compared to $<1.8$ without it.

Du Pont Krytox 143 AB (containing a corrosion inhibitor) and Dow Corning XF-1-0301 are both rated second best of the lubricants tested. Only two bearings were run with Krytox 143 AB in a 50 hour film measuring test and both bearings were in good condition with the exception of some small micropitted areas on one outer-ring and a slightly uneven wear track on the second outer-ring.

All six bearings run with Dow Corning XF-1-0301 lubricant exhibited a minor degree of glazing and micropitting. However, this lubricant experienced the highest viscosity increase, 45%, of any of the lubricants tested which is attributed to the "boiling off" of the higher volability and/or lower viscosity components.

The next two lubricants, both ranked third, are Mobil XRM-109F plus 10% Kendall Resin and Monsanto MCS-2931. All six bearings run with the former lubricant achieved time-up life and exhibited moderate to heavy micropitting and generally light glazing after testing. These results show an improvement over results of tests run using straight Mobil XRM-109F which were characterized by severe glazing in the bearing raceways. The drastic reduction and in some cases complete elimination of the glazing type surface distress is a beneficial effect on using the Kendall Resin as an additive in XRM-109F.

Only two of six bearing run with MCS-2931 lubricant reached time-up life and two other bearings suffered inner-ring spalling failures. Typical appearance of the bearing tested with MCS-2931 include moderate to heavy pitting, with micro-pitting in the vicinity of surface defects such as honing tears and debris dents. Little, if any, glazing was seen in the bearings. A 22% viscosity increase was noted for this lubricant after testing. Considering the general lack of glazing-type surface distress with MCS-2931 it appears that this fluid probably provides marginally adequate boundary lubrication however, considering the presence of micropitting at surface defects it would seem that this fluid may be somewhat more sensitive and prone to failures which arise in the vicinity of inclusions in the metal or bearing surface defects.

Three lubricants are ranked fourth as shown in the above tabulation; Esso AL07873, Humble FN-3158, and Mobil XRM-109F in slightly decreasing order.

The six bearings run with Esso AL07873 lubricant achieved the prescribed time-up life, however, ball spalling and pitting were noted along with moderate to heavy glazing in the bearing raceways. The lubricant showed good stability in resistance to viscosity and acidity changes. However, the fluid turned from clear to black after testing despite the very low oxygen concentration maintained within the rig.

Two of six bearings tested with Humble FN-3158 lubricant reached time-up life but one of these bearings was found spalled upon disassembly. One other bearing was spalled in both rings and a third bearing was smeared. Typical appearance of bearings tested with FN-3158 lubricant includes extensive pitting on both inner and outer rings. On the basis of this performance, this fluid (unblended) is judged unsatisfactory for full scale testing of jet-engine mainshaft-size bearings. However, as previously noted, drastically improved performance is obtained with this lubricant through the addition of 10% Kendall Resin.

Severe glazing was recorded in the screening tests with Mobil XRM-109F lubricant. Much is known from previous programs (1, 2, 3) on the performance of this fluid and these results are not unexpected. This fluid was, in fact, used primarily as a baseline for all testing on this program. Despite the presence of heavy glazing in the screening tests which is indicative of lowered film thickness ($h/\sigma < 2$), there was very little, if any, glazing in the film measuring test with measured $h/\sigma$ values on the order of 3.5 to 4.0 at 600°F (589°K). These later results are not typical for this fluid under the test conditions used and it is thought that the less severe start-up conditions for the film measuring tests as compared to the screening tests (see Test Procedure Section) may have contributed to the situation. This fluid (unblended) is therefore also considered unsuitable for full scale tests of jet-engine mainshaft-size bearings. However, as with FN-3158 lubricant, the performance of XRM-109F can be significantly enhanced, especially in the reduction and elimination of glazing type surface distress, through the addition of 10% Kendall Resin.

## DISCUSSION OF LUBRICANT BEHAVIOR

### 1. Mobil XRM-109F

Much is known about the performance of this lubricant from the results of previous programs conducted within the Laboratory (2, 3, 6). In general, testing with this lubricant and 7205 size bearings has usually resulted in glazing type surface distress, similar to that seen in the present screening tests, and in some instances has also led to bearing smearing failures. Short term lubricant film thickness measurements taken over a wide range of temperatures during one of these previous programs (3) gave an $h/\sigma$ value of 2 to 3 for the test conditions used here. The lower of the two $h/\sigma$ values indicates operation in the lower partial EHD region where there are substantial numbers of asperity contacts which may lead to glazing and smearing depending on boundary lubrication conditions. Mobil XRM-109F does not contain a boundary lubrication additive and therefore the glazing phenomenon noted with this lubricant is understandable. Moreover, tests run with Mobil XRM-177F (XRM-109F containing a proprietary boundary lubricant additive) have resulted in a drastic reduction of glazing type surface distress further indicating that operation with XRM-109F at 600°F (589°F) is in the partial boundary EHD regime.

In the film measuring test with this fluid high $h/\sigma$ values were recorded (3.5-4.0). This is surprising since values of 2.0 to 3.0 were obtained on a previous program (3) and since tests with this lubricant typically produce extensive glazing of the races. It should be noted, however, that the bearings used on this particular test were in good condition and did not show any glazing. It appears then that the unexpectedly high film thicknesses to roughness ratio are explained by the absence of the local roughening of the surface associated with glazing. Since film measuring tests subject the bearings to considerably less acceleration that screening tests and since the acceleration rate is not strictly uniform from one film measuring test to the next, (see Test Procedure Section), this particular film test may have avoided the early onset of glazing with the resultant high film thickness/roughness ratio.

2. Monsanto MCS-2931

EHD film measurements with this polyphenyl ether lubricant resulted in film parameter values of $h/\sigma < 1.8$ at 600°F (589°K) indicating bearing operation in the lower partial EHD region. Under these conditions, one would normally expect the tested bearings to show the rather heavy glazing-type surface distress which was so evident on the bearings tested with Mobil XRM-109F. However, only normal slight glazing and micropitting around surface defects such as furrows was observed. These results indicate that MCS-2931 provides marginally adequate boundary lubrication protection for smooth surfaces but local breakdown of boundary lubrication occurs at surface irregularities resulting in the glazing and micropitting shown in Enclosure 24.

Continued operation where these conditions are present could lead to surface initiated spalling failures, as did occur with the lubricant in two of the tests at bearing lives of 46.9 hrs. and 42.8 hours (121 and 111 mill.revs.). The mechanism for the formation of such surface initiated spalling failures is quite complex. It has been shown analytically by Chiu ( 9 ), that surface irregularities produce variations in the stress field which can induce local plastic stresses to occur below the surface. The occurrence of plastic flow has been verified in this area by the observation of structural alterations indicative of plastically deformed material, around such surface defects, by Martin, et al (10). The presence of such highly stressed material would significantly reduce the life of spalling failures in this volume of material, since it is a direct function of stress. Once surface micro-cracks are formed the stress picture is again altered and spall propagation can be accelerated. At all stages of this sequence of events lubricant effects are quite important.

The influences of lubricant chemistry on fatigue life are as yet not well understood, though a variety of hypotheses have been suggested, for example in (11) to explain the effects of different lubricants. For example, it has been suggested that:

1. Hydrogen formed by chemical reactions at the crack tip may cause highly localized embrittlement of the steel.

2. Protective coatings formed by some lubricants may reduce or prevent penetration of fluid into the cracks, whereas other coatings may be less effective in this respect.

3. Boundary lubricant films formed by reaction of the lubricant with the metal surfaces control tractive forces and welding at surface asperity or defect interaction sites, thus relieving the severity of plastic flow in the metal and subsequent crack initiation and propagation. Variation of tractive forces could also affect heat generation and localized film thickness.

4. The surface active characteristics of the lubricant may affect the plastic properties (yield strength, ductility) of the plastically flowing metal at surface defects and asperity interactions, and thus influence cracking behavior.

<u>3. Humble FN-3158 (Super Refined Mineral Oil)</u>

In the film measuring test with this candidate lubricant, $h/\sigma$ ranged from 2.6 to 3.6 during the first 11.1 hours of operation and then, following a scheduled shutdown and subsequent restart films were below the measurable level, $h/\sigma < 1.8$ for the remaining 38.9 hours of operation, again indicating bearing operation in the lower partial EHD region during most of the test. The various bearings tested with this lubricant contained light to heavy pitting, small and large spalls, glazing, micropitting, and one smearing failure indicating poor overall performance. Pitting of the raceways was common to the bearings run in the screening tests with halos of glazing and micropitting surrounding the pits. Since gross glazing of the bearing raceways was not generally noted despite the low film parameter value for 600°F (589°K) operation, it can be concluded that FN-3158 provides marginal boundary lubrication.

Since this fluid does not have a kinematic viscosity sufficiently high to prevent asperity interaction (0.75 cs at 600°F, (589°K) $h/\sigma < 1.8$) and does not have adequate boundary lubricating properties to compensate for this lack, the use of FN-3158 lubricant for high speed, high temperature bearing applications cannot be recommended.

4. Humble FN-3158 Plus 10% Kendall Resin

This blended lubricant proved to be the best of the eight candidate lubricants tested. Measured film parameter values ranged from $h/\sigma = 3.6$ to 4.0 at 600°F (589°K) (compared to $<1.8$ for the FN-3158 alone) and all bearings tested were in good condition with the exception of one bearing which was lightly micropitted. It is thought that the greatly increased film thickness and much improved behavior is caused by the Kendex resin significantly increasing the viscosity in the Hertzian contact areas. These results show a definite improvement over results obtained with straight FN-3158 and demonstrates performance at least comparable to the best lubricant found from previous programs (2, 6, 7), Mobil XRM-177F. Previous results with XRM-177F showed some glazing-type surface distress on comparable M50 steel bearings after 180 hours (464 mill. revs.) of operation at 600°F (589°K) whereas with FN-3158 plus 10% Kendall Resin, no glazing at all was noted after 100 hours (258 mill. revs.) of operation at 600°F (589°K). Chemically this blended fluid was very stable in resistance to changes in viscosity, acidity, and dirt content as can be seen from lubricant sample analysis data given in Appendix III. This lubricant blend is definitely recommended for use in full scale testing of jet engine mainshaft bearings or in critical small bearing applications.

Since this fluid gave such good results at 600°F, (589°K), it would be most interesting to run a future test series at 700°F (644°K) determine the practical temperature limit of the fluid and also possibly include open atmosphere testing if an effective oxidation inhibitor could be used.

### 5. Dow Corning XF-1-0301 (Modified Fluorosilicone)

Dow Corning XF-1-0301 is one of two lubricants rated second best of the candidate lubricants tested on the basis of bearing condition. However, this lubricant experienced the highest viscosity increase after 100 hours of testing which may indicate some thermal instability at 600°F (589°K) or simply the "boiling off" of the higher volatility and/or lower viscosity components. Evidently this bulk viscosity increase, presumed to have occurred gradually resulted in no harmful effects since bearing condition after 100 hour tests was no worse than bearing condition after the 50 hour test: all tested bearings had some light pitting and remained in serviceable condition. The film parameter value was below the measureable level indicating $h/\sigma < 1.8$ for the entire 50 hour film measuring test which was lower than expected based on the condition of the tested bearings from the screening tests. It was thought at one time that the fluid itself might be conductive thus resembling metal to metal contact to the film measuring system since the Hertzian contacts were electrically shorted. Simple beaker tests conducted at open atmosphere and room temperature using the film instrumentation showed the lubricant to be non-conductive, however, this may not accurately reflect its condition in a high temperature, high pressure Hertzian contact.

Based on results in this program, this lubricant is recommended for use in full scale jet engine mainshaft bearing tests.

### 6. Mobil XRM-109F plus 10% Kendall Resin

All six bearings tested with XRM-109F plus 10% Kendall Resin lubricant achieved time-up life as shown in the test results with final bearing condition showing an improvement over tests run with straight XRM-109F, especially in the reduction of the glazing surface distress. Typical bearing raceway condition includes glazing with light to heavy micropitting and two bearings were found to have spalled balls.

Comparing results of tests run with FN-3158 plus 10% Kendall Resin and XRM-109F plus 10% Kendall Resin it is seen that a much more drastic improvement over the base lubricant performance occurred in the former case than in the latter case. It was mentioned in the previous sections that FN-3158 probably provides some degree of boundary lubrication whereas XRM-109F provides very little or no boundary lubrication. It is thought that this difference may have contributed to the superior performances mentioned above.

## 7. Esso AL07873 (Highly Hindered Ester)

Results obtained with this lubricant were somewhat unusual in that ball spalling failures were very common occurrences. In fact, all tested bearings contained spalled balls. Evidently, the vibroswitch setting did not give the required sensitivity to detect the spalled balls and all bearings ran to time up life. Consequently the races were dented from rolling of the spalled balls. The races typically contained moderate to very heavy glazing with pitting and micropitting.

The film parameter value was below the measurable level indicating $h/\sigma < 1.8$, for the entire 50 hour film measuring test. The film parameter value corresponds with the observed condition of the tested bearings. The degree of glazing seen with this lubricant is second only to that noted for XRM-109F and is considered excessive. The ball spalling phenomenon may be the result of a high stress concentration in the balls due to the contact pressure profile obtained with this lubricant or from an unexpected kinematic or chemical reaction with the bearing due to some unidentified property of the lubricant.

The performance of AL07873 lubricant in full scale mainshaft bearing tests is questionable. Marginal performance and some surface distress of the test bearing makes good performance appear unlikely on the basis of present information.

## 8. DuPont Krytox 143AB (Perfluoro Alkyl Polyether)

In the one film measuring test run with this lubricant, the film parameter value started out initially at a value of 3.0 and rose to 4.0 over a period of 7.6 hours indicating full EHD lubrication. Over the next hour, film thickness dropped to below the measurable level, $h/\sigma < 1.8$, and remained as such for the rest of the 50 hour test. After the test, the bearings were visually inspected and found to be in generally good condition, second only to bearings run with the best lubricant tested, FN-3158 plus 10% Kendall Resin, but did contain some small localized areas of micropitting. Also, the ball track of one outer ring was slightly irregular which seems to happen more often with this lubricant than with the others tested based on these results and on results of a previous program (3).

It is possible to hypothesize that rheological properties of this lubricant result in a lessening of ball-race tractive forces and may induce an unknown degree of ball sliding which results in high local heat generation which would show up as the decrease of the film parameter value as was the case in the present test. This excessive spinning and consequent film reduction could then manufest itself as localized micropitting or glazing.

The Krytox 143 AB tested on this program contained an additive to limit corrosion as described in the Test Lubricants Section. In a recent program (3) Krytox 143 AC without the additive was tested and film thickness measurements were made. Results with both lubricants were comparable indicating no beneficial or detractive effects in bearing performance, measured by bearing condition, resulting from the use of the corrosion limiting additive.

Krytox 143 AC (without the additive) had been previously tested on another program (11) with good success at temperatures up to 700°F (644°K) with mainshaft size bearings. Examination of these past results at 700°F (644°K) shows good correlation with results of the present 600°F (589°K) tests and further gives support to the practice of subjecting advanced candidate lubricants to screening tests with 25-mm bearings prior to more expensive full scale tests with mainshaft size bearings.

## CONCLUSIONS

1. The eight candidate lubricants evaluated on this program are ranked as follows on the basis of their acceptability for further full scale testing with mainshaft size bearings.

a. excellent - Humble FN-3158 plus 10% Kendall Resin

b. good - DuPont Krytox 143AB (with additive) and Dow Corning XF-1-0301

c. acceptable - Mobil XRM-109F plus 10% Kendall Resin, Monsanto MCS-2931

d. unacceptable - Esso AL07873, Humble FN-3158, Mobil XRM-109F

2. The tests conducted on this program using 25 mm bearings have been shown to be generally more severe than full scale tests conducted on another program using 125 mm mainshaft bearings. Mobil XRM-109F plus 10% Kendall Resin gave very good results with the latter size bearings and produce marginal to good results at comparable temperatures with 25 mm bearings. This result provides verification for the screening of candidate mainshaft lubricants by running in the scaled down rigs. These scaled down rig tests give results relatively quickly and are considerably more economical than full scale mainshaft tests.

3. The performance of selected mineral oil and synthetic hydrocarbon base lubricants such as Humble FN-3158 and Mobil XRM-109F respectively may be significantly enhanced, especially in the reduction or elimination of bearing raceway surface distress, by the addition of 10% Kendall Special Resin 0839.

4. While a substantial lubricant film thickness is desirable to prevent asperity interactions, chemical properties of the lubricant are also quite important, especially when manifested as the ability to prevent surface initiated spalling under glazing conditions and other forms of surface distress which could lead to early failure when bearing operation is in the partial EHD region. For example, performance of the highly refined mineral oil was unsatisfactory during operation in partial EHD region when failures occurred due to surface distress from numerous asperity interactions under poor boundary lubricating conditions. This deficit was overcome by the addition of Kendex Resin which increased film thickness and

moved operation into the region where good boundary lubricating properties were not necessary (or perhaps provided improved boundary lubricating characteristics). In contrast to this, the modified fluorosilicone permitted operation in the partial EHD region due to it's good boundary lubricating properties.

# APPENDIX I

## PROPERTIES OF CANDIDATE LUBRICANTS (EXCLUDING PROPRIETARY SPECIFICATIONS).

### 1. Mobil XRM-109F (Synthetic Hydrocarbon)

Kinematic Viscosity

| °F | CS ($m^2$/sec X $10^6$) |
|---|---|
| 0 (255°K) | 37,000 |
| 100 (311°K) | 447. |
| 210 (372°K) | 40.4 |
| Total Acid No. | 0.0 |
| Flash Point | 520°F (544°K) |
| Fire Point | 595.°F (586°K) |
| Pour Point | -60.°F (222°K) |

Density

| °F | g/ml |
|---|---|
| 100 (311°K) | .8389 |
| 200 (366°K) | .8082 |
| 300 (422°K) | .7777 |
| 400 (478°K) | .7428 |
| 500 (533°K) | .7140 |

Specific Heat

| °F | BTU/lb.°F | |
|---|---|---|
| 100 (311°K) | .521 | 2180 J/kg C° |
| 300 (422°K) | .635 | 2657 J/kg C° |
| 400 (478°K) | .692 | 2895 J/kg C° |
| 500 (533°K) | .750 | 3138 J/kg C° |

### 2. Monsanto MCS-2931 (Improved MCS-293, Polyphenyl Ether)

Kinematic Viscosity

| °F | CS ($m^2$/sec X 106) |
|---|---|
| 0 (255°K) | 12,785 |
| 100 (311°K) | 24.2 |
| 210 (372°K) | 4.1 |
| Acid No. | .23 |

APPENDIX I (Continued)

| | | |
|---|---|---|
| Flash Point | 480°F | (522°K) |
| Fire Point | 540°F | (555°K) |
| Pour Point | -20°F | (244°K) |
| Density | | |

| °F | | g/ml |
|---|---|---|
| 0 | (255°K) | 1.225 |
| 100 | (311°K) | 1.183 |
| 300 | (422°K) | 1.100 |
| 500 | (533°K) | 1.016 |
| 600 | (589°K) | .972 |

Specific Heat

| °F | | BTU/lb.°F | |
|---|---|---|---|
| 0 | (255°K) | .312 | 1,305 J/kgC° |
| 100 | (311°K) | .347 | 1,452 |
| 200 | (366°K) | .383 | 1,602 |
| 300 | (422°K) | .418 | 1,749 |
| 400 | (478°K) | .452 | 1,891 |
| 500 | (533°K) | .488 | 2,042 |
| 600 | (589°K) | .523 | 2,188 |

## 3. Humble FN-3158 (Super-Refined Mineral Oil)

Kinematic Viscosity

| °F | | CS | ($m^2$/sec X $10^6$) |
|---|---|---|---|
| 0 | (255°K) | 10,289 | |
| 100 | (311°K) | 78.08 | |
| 200 | (366°K) | 8.238 | |

| | | |
|---|---|---|
| Acid No. | 2.01 | |
| Flash Point | 445°F | (503°K) |
| Fire Point | 485°F | (525°K) |
| Pour Point | -30°F | |
| Density | | |

APPENDIX I (Continued)

| °F | | g/ml |
|---|---|---|
| 0 | (255°K) | .908 |
| 200 | (366°K) | .838 |
| 400 | (478°K) | .768 |

Specific Heat

| °F | | BTU/lb.°F | |
|---|---|---|---|
| 0 | (255°K) | .423 | 1,770 J/kg C° |
| 200 | (366°K) | .517 | 2,163 |
| 400 | (478°K) | .610 | 2,552 |

4. Humble FN-3158 plus 10% Kendall Heavy Resin (For Humble FN-3158 data, see 3.)

Kendall Heavy Resin:
Kinematic Viscosity

| °F | | CS ($m^2$/sec X $10^6$) | |
|---|---|---|---|
| 100 | (311°K) | 6618.8 | |
| 210 | (372°K) | 221.7 | |
| Flash Point | | 640°F | (611°K) |
| Fire Point | | 715°F | (653°K) |
| Pour Point | | 20°F | (266°K) |

Density

| °F | | gms/cc |
|---|---|---|
| 60 | (289°K) | .902 |

Humble FN-3158 plus 10% Kendall Resin

Kinematic Viscosity

100°F (311°K) 112.40 cs ($m^2$/sec X $10^6$)

Acid Number .02

APPENDIX I (Continued)

5. Dow Corning XF-1-0301 (Modified fluorosilicone)

Specific Data

Kinematic Viscosity

| °F | CS ($m^2$/sec X $10^6$) |
|---|---|
| 77 (298°K) | 42.4 |
| 100 (311°K) | 26.4 |
| 210 (372°K) | 5.98 |
| Acid No. | No Trace |
| Flash Point | 485°F (525°K) |
| Fire Point | 525°F (547°K) |
| Specific Heat @ 25°F (269°K) | .366 Btu/lb. °F 1531 J/kg °C |

Typical Data

Kinematic Viscosity

| °F | CS ($m^2$/sec X $10^6$) |
|---|---|
| 77 (298°K) | 50 |
| 100 (311°K) | 29 |
| 210 (372°K) | 6.2 |
| Acid Number | 0.01 |
| Flash Point, open cup | 440°F. (500°K) |
| Fire Point | 490°F. (528°K) |
| Spontaneous Ignition Temperature | 880°F. (744°K) |
| Pour Point | -85°F. (208°K) |
| Incipient Thermal Decomposition | 625°F. (603°K) |
| Specific Gravity @ 77°F. (298°K) | 1.15 |

6. Mobil XRM-109F plus 10% Kendall Heavy Resin (For Mobil XRM-109F, see a. For Kendall Resin, see d)
Mobil plus Kendall Resin
Kinematic Viscosity @ 100°F (311°K) 550.4 cs ($m^2$/sec X $10^6$)
Acid No. .05

F-4186 A R 100

APPENDIX I (Continued)

7. Esso AL07873 (Highly Hindered Ester)
Kinematic Viscosity

| °F | | CS ($m^2$/sec X $10^6$) | |
|---|---|---|---|
| -40 | (233°K) | 12,799 | |
| 100 | (311°K) | 30.01 | |
| 210 | (372°K) | 5.289 | |
| Acid No. | | .06 | |
| Flash Point | | 480°F | (522°K) |
| Pour Point | | 70°F | (294°K) |

8. DuPont Krytox 143AB- Containing a proprietary Additive
(Perfluoro Alkyl Polyether)

Kinematic Viscosity

| °F | | CS ($m^2$/sec X $10^6$) | |
|---|---|---|---|
| 0 | (255°K) | 6900 | |
| 100 | (311°K) | 85 | |
| 210 | (372°K) | 10.3 | |
| Pour Point | | -45°F | (230°K) |

Density

| °F | | gm/ml |
|---|---|---|
| 75 | (297°K) | 1.89 |
| 210 | (372°K) | 1.76 |
| 400 | (478°K) | 1.57 |

APPENDIX II

## DETAILED DESCRIPTION OF TESTED BEARINGS

MOBIL XRM-109F

| Bearing | Part | Description |
|---|---|---|
| 101 | IR | Highly glazed; pitting extending 360° around ring, width of band approximately equal to the major axis of the contact ellipse. |
| | OR | Very highly glazed; band of pitting extending 360° around ring; width of band approximately 1/2 again larger than above but pitting not as severe; some honing tears. |
| | Balls | Lightly shallow pitting. |
| 102 | IR | Highly glazed, wide wear track, wide band of moderate to heavy pitting. |
| | OR | Highly glazed wide wear track, wide band of heavy pitting and small spalls. |
| | Balls | Spalled ball, some denting, glazing and micropitting. |
| 103 | IR | Highly glazed, moderate to heavy pitting. |
| | OR | Highly glazed, moderate pitting & micro pitting, honing tears. |
| | Balls | Micropitted, some heavy pitting. |
| 104 | IR | Very highly glazed; moderate to heavy pitting. |
| | OR | Highly glazed; moderate pitting & micro pitting, honing tears. |
| | Balls | Micropitted. |
| 105 | IR | Wear track 50% oversize (width); raceway "frosted" with some light pitting. |
| | OR | Wear track uneven (2 places); otherwise good condition. |
| | Balls | Some slight debris pitting but otherwise good condition. |

| | | |
|---|---|---|
| 106 | IR | No glazing; some denting, some honing tears. (black oxide coated bearing). |
| | OR | Wear track uneven, no glazing, some honing tears and debris denting. |
| | Balls | good condition. |
| 105*(aborted) | IR | Highly glazed; pitted completely around ring (not pitted as badly as #101 or 104). |
| | OR | Highly glazed; 360° band of pitting, wear track irregular. |
| | Balls | Glazed lightly; pitted and dented. |
| 106*(aborted) | IR | Glazed & lightly pitted. |
| | OR | Uneven wear track, no glazing. |
| | Balls | Light denting only. |

MONSANTO MCS-2931 Dulited

| | | |
|---|---|---|
| 201 | IR | No glazing; some micropitting around honing tears; generally good condition. |
| | OR | Lightly glazed, heavy denting, micropitting around honing tears. |
| | Balls | Some light pitting on balls. |
| 202 | IR | Spalled with light glazing. |
| | OR | Heavy debris denting. |
| | Balls | Good condition. |
| 203 | IR | No glazing, some debris denting. |
| | OR | No glazing, some micropitting. |
| | Balls | Some debris denting and micropitting. |

| | | |
|---|---|---|
| 205 | IR | Extensive micropitting. |
| | OR | Moderate glazing and micropitting; slightly uneven wear track |
| | Balls | Light glazing and rather heavy micropitting |
| 206 | IR | Large spall, remainder of groove has some pitting and debris denting, no glazing. |
| | OR | Very heavily dented - no glazing - micro pitting around some honing tears. |
| | Balls | No glazing - some very light pitting. |
| 205*(aborted) | IR | Moderate pitting, honing tears, no glazing except in vicinity of honing tears. |
| | OR | Uneven wear track; scattered pitting, serviceable condition. |
| | Balls | Some deep pitting. |
| 206*(aborted) | IR | Good condition except for some localized debris denting. |
| | OR | No glazing, some localized heavy pitting, and denting. |
| | Balls | Sporatic pitting. |

HUMBLE FN-3158

| | | |
|---|---|---|
| 301 | IR | Smeared. |
| | OR | Smeared. |
| | Balls | Smeared. |
| 302 | IR | Band of heavy pitting 360° around ring, some pitts look large enough to be considered small spalls; glazing in vicinity of pits only. |
| | OR | Pitted 360° around ring; glazing in vicinity of pits only. |
| | Balls | Moderate to heavy debris denting. |
| 303 | IR | Band of heavy pitting 360° around ring glazing in vicinity of pit |
| | OR | Debris dents. |
| | Balls | Debris dents. |

| | | |
|---|---|---|
| 304 | IR | Heavy spall; some minor spalling and heavier pitting all around ring. |
| | OR | Several small spalls and heavier pitting all around ring; moderate to heavy glazing. |
| | Balls | Few heavy pits. |
| 305 | IR | Small Spall; otherwise good condition |
| | OR | Heavily micropitted all around groove; slightly uneven wear track. |
| | Balls | Micropitted. |
| 306 | IR | Good condition; no glazing or pitting; some light debris denting. |
| | OR | No surface distress; debris pits & debris dents. |
| | Balls | Light to moderate debris pits and dents. |

FN-3158 PLUS KENDALL RESIN

| | | |
|---|---|---|
| 401 | IR | Some debris dents and micropitting. |
| | OR | Light debris dents and micropitting. |
| | Balls | Micropitted and debris dented. |
| 402 | IR | Good condition; with light debris dents. |
| | OR | Good condition with some debris dents. |
| | Balls | Good condition with light debris dents. |
| 403 | IR | Some debris denting. |
| | OR | Some debris denting. |
| | Balls | Debris dented. |
| 404 | IR | Some light localized micropitting but rest of ring in good condition; no glazing. |
| | OR | Good condition with some light debris denting. |
| | Balls | Light debris denting. |
| 405 | IR | Good condition. |
| | OR | Good condition. |
| | Balls | Good condition. |

| | | |
|---|---|---|
| 406 | IR | Good condition. |
| | OR | Good condition with some light debris denting. |
| | Balls | Good condition. |

DOW CORNING XF-1-0301

| | | |
|---|---|---|
| 501 | IR | Glazed and micropitted. |
| | OR | Glazed and micropitted. |
| | Balls | Micropitted. |
| 502 | IR | Ring has 360° band of micropitting, uneven wear track. |
| | OR | Good condition. |
| | Balls | Good condition. |
| 503 | IR | Very light micropitting |
| | OR | Glazed and micropitted |
| | Balls | Heavy micropitting |
| 504 | IR | Light to moderate pitting with some glazing; generally good. |
| | OR | Good condition with light micropitting. |
| | Balls | Light pitting. |
| 505 | | |
| | IR | Moderate micropitting but otherwise good condition. |
| | OR | Very light micropitting but otherwise good condition. |
| | Balls | Moderate glazing & micropitting; minor pitting. |
| 506 | IR | Good condition with light debris pits. |
| | OR | Slightly uneven wear track; light debris pits; no glazing; ring generally in good condition. |
| | Balls | Debris denting. |

F-4186 A R 100

MOBIL XRM-109F PLUS 10% KENDALL RESIN

| | | |
|---|---|---|
| 601 | IR | Glazed and micropitted extensively. |
| | OR | Glazed and micropitted extensively. |
| | Balls | Some micropitting. |
| 602 | IR | Severe micropitting. |
| | OR | Some micropitting and debris denting. |
| | Balls | Two spalled balls and some micropitting. |
| 603 | IR | Glazed and micropitted extensively. |
| | OR | Glazed and micropitted extensively. |
| | Balls | Micropitting on all balls. |
| 604 | IR | Highly glazed & heavily micropitted 360° around ring. |
| | OR | Glazing and heavy micropitting 360° around ring. |
| | Balls | Glazed and micropitted. |
| 605 | IR | Moderate to heavy micropitting 360° around ring; but no heavy pits and bearing still serviceable. |
| | OR | Extensive micropitting but still serviceable. |
| | Balls | All balls have light to heavy pitting; two balls spalled. |
| 606 | IR | Generally good condition with very little glazing and a light band of micropitting. |
| | OR | Generally good condition with a light band of micropitting. |
| | Balls. | Good condition. |

HUMBLE AL07873

| | | |
|---|---|---|
| 701 | IR | Moderate glazing and pitting. |
| | OR | Heavy glazing with moderate pitting & micropitting. |
| | Balls | One spalled, all balls moderately glazed. |
| 702 | IR | Moderately glazed with light pitting and heavier micropitting. |
| | OR | Moderate to heavy glazing, micropitting, and debris denting. |
| | Balls | One spalled; all balls highly glazed; no pitting. |

| | | |
|---|---|---|
| 703 | IR | Moderately glazed with moderate to heavy pitting; light to moderate debris denting. |
| | OR | Moderate to heavy glazing; moderate to heavy pitting and micropitting; light debris denting. |
| | Balls | Small spalls on all balls; moderate pitting on all balls. |
| 704 | IR | Highly glazed with light pitting (good condition except for glazing). |
| | OR | Extensive glazing; no pitting. |
| | Balls | Two balls have small spalls, three balls are pitted and all balls are heavily glazed. |
| 705 | IR | Highly glazed with moderate pitting and micropitting. |
| | OR | Highly glazed with moderate pitting and micropitting. |
| | Balls | All balls highly glazed and spalled. |
| 706 | IR | Moderate to heavy glazing with light pitting. |
| | OR | Moderate to heavy glazing with light pitting. |
| | Balls | Moderately glazed and pitted, two spalled. |
| 805 | IR | Good condition. |
| | OR | Areas of light glazing and micropitting. |
| | Balls | Light micropitting. |
| 806 | IR | Very light micropitting. |
| | OR | Light micropitting with slightly uneven wear track. |
| | Balls | Light micropitting. |

# APPENDIX III

## OIL SAMPLE ANALYSIS DATA

| Lubricant | Test No. | Time Hrs. | Visc. CS, + $m^2$ X $10^6$ @ 100°F | Dirt Content gms/100 ML | Acid No. |
|---|---|---|---|---|---|
| Mobil XRM 109F | 1A | unused | 445.0 | 0.01 | .05 |
| | | 2 | 448.3 | 0.07 | .09 |
| | | 10 | 468.9 | 0.09 | .08 |
| | | 14.3 | 458.8 | 0.06 | .07 |
| Monsanto MCS 2931 | 2B | 2 | 25.4 | 0.07 | .07 |
| | | 10 | 26.6 | 0.02 | .04 |
| | | 50 | 28.2 | 0.02 | .08 |
| | | 100 | 29.6 | 0.02 | .08 |
| Humble FN 3158 | 3A | unused | 77.6 | 0.002 | .03 |
| | | 2 | 100.9 | 0.01 | .06 |
| | | 10 | 84.1 | 0.01 | .07 |
| | | 50 | 111.9 | 0.004 | .06 |
| | | 71.7 | 107.6 | 0.06 | .03 |
| Humble FN 3158 + 10% Kendall Resin | 4A | unused | 112.4 | 0.02 | .02 |
| | | 2 | 131.8 | 0.02 | .02 |
| | | 10 | 144.3 | 0.02 | .02 |
| | | 50 | 151.1 | 0.02 | .02 |
| | | 100 | 128.2 | 0.02 | .02 |
| Dow Corning XF1-0301 | 5B | unused | 26.5 | 0.02 | .07 |
| | | 2 | 26.6 | 0.02 | .09 |
| | | 10 | 27.2 | 0.02 | .08 |
| | | 50 | 36.8 | 0.02 | .06 |
| | | 100 | 38.3 | 0.02 | .06 |
| Mobil XRM 109F + 10% Kendall Resin | 6B | unused | 550.3 | 0.01 | 0.05 |
| | | 2 | 585.2 | 0.02 | 0.05 |
| | | 10 | 630.2 | 0.01 | 0.08 |
| | | 50 | 653.5 | 0.02 | 0.07 |
| | | 100 | 650.8 | 0.01 | 0.07 |

## APPENDIX III (Continued)

## OIL SAMPLE ANALYSIS DATA

| Lubricant | Test No. | Time Hrs. | Visc. CS, + $m^2/sec \times 10^6$ @ 100°F | Dirt Content gms/100 ML | Acid No. |
|---|---|---|---|---|---|
| Esso AL07873 | 7A | unused | 29.5 | .006 | .03 |
| | | 2 | 28.6 | .002 | .04 |
| | | 10 | 32.0 | .004 | .06 |
| | | 50 | 30.8 | .005 | .05 |
| | | 100 | 31.4 | .003 | .03 |
| Krytox 143 AB (with additive) | 8C | unused | 95.9 | 1.10 | .03 |
| | | 50 | 107.6 | 2.16 | .06 |

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RESEARCH LABORATORY SKF INDUSTRIES, INC.

APPENDIX IV

BEARING/OIL IN AND OIL OUT TEMPERATURE DATA

| TEST NO. | TIME HRS. | DRIVE BEARING OIL IN °F | °R | OIL OUT °F | °R | O.R. °F | °R | LOAD BEARING OIL IN °F | °R | OIL OUT °F | °R | I. R. °F | °R | O. R. °F | °R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1A Mobil XRM-109F | 0.0 | 555 | 564 | 660 | 622 | 538 | 554 | 536 | 553 | 538 | 554 | 610 | 594 | 523 | 546 |
| | 10.1 | 600 | 589 | - | - | - | - | 595 | 586 | 554 | 563 | 600 | 589 | 589 | 583 |
| | 13.1 | 615 | 597 | - | - | - | - | 601 | 589 | 555 | 564 | 595 | 586 | 594 | 585 |
| | 14.1 | | | | | F - A - I - | | L - E - D | | | | | | | |
| 1B | 0.1 | | | | | | | | | | | 565 | 569 | | |
| | 0.3 | | | | | F - A - I - | | L - E - D | | | | | | | |
| 1C | .1 | | | | | | | | | | | | | 480 | 522 |
| | 6.8 | 589 | 583 | 598 | 588 | 568 | 571 | 589 | 583 | 560 | 566 | - | - | 600 | 589 |
| | 22.8 | 595 | 586 | 603 | 590 | 593 | 585 | 586 | 581 | 579 | 577 | - | - | 593 | 585 |
| | 29.8 | 599 | 588 | 597 | 587 | 593 | 585 | 586 | 581 | 568 | 571 | - | - | 596 | 586 |
| | 39.8 | 619 | 599 | 625 | 603 | 598 | 586 | 609 | 594 | 603 | 596 | - | - | - | - |
| | 49.4 | 608 | 593 | 617 | 598 | 593 | 585 | 592 | 584 | 587 | 581 | - | - | 604 | 591 |
| 2A Monsanto MCS-2931 | 0.0 | 435 | 497 | - | - | 438 | 499 | 444 | 502 | 458 | 510 | 470 | 516 | 439 | 499 |
| | 9.8 | 530 | 548 | 551 | 561 | 530 | 550 | 545 | 558 | 552 | 562 | 510 | 539 | 543 | 557 |
| | 20.0 | 595 | 586 | 628 | 604 | 602 | 590 | 604 | 591 | 608 | 593 | 635 | 608 | 602 | 590 |
| | 30.0 | 602 | 590 | 638 | 610 | 611 | 595 | 608 | 593 | 613 | 596 | 635 | 608 | 610 | 594 |
| | 40.0 | 590 | 583 | 620 | 600 | 599 | 588 | 597 | 587 | 607 | 593 | 625 | 608 | 598 | 588 |
| | 46.5 | 587 | 581 | 626 | 603 | 603 | 590 | 586 | 581 | 596 | 586 | 610 | 594 | 583 | 579 |
| | 46.9 | | | | | F - A - I - | | L - E - D | | | | | | | |
| 2B | .3 | 577 | 576 | 590 | 583 | 574 | 574 | 586 | 581 | 582 | 579 | 610 | 594 | 566 | 570 |
| | 10.7 | 612 | 595 | 597 | 587 | 611 | 595 | 604 | 591 | 604 | 591 | 615 | 597 | 594 | 585 |
| | 20.6 | 587 | 581 | 592 | 584 | 597 | 587 | 604 | 591 | 607 | 593 | 625 | 603 | 599 | 588 |
| | 30.5 | 596 | 586 | 621 | 600 | 607 | 593 | 606 | 592 | 607 | 593 | 630 | 605 | 598 | 588 |
| | 40.5 | 589 | 583 | 622 | 601 | 595 | 586 | 604 | 591 | 606 | 592 | 625 | 603 | 595 | 586 |
| | 50.5 | 595 | 586 | 628 | 604 | 600 | 589 | 603 | 590 | 606 | 592 | 620 | 600 | 592 | 584 |
| | 60.5 | 598 | 588 | 629 | 605 | 605 | 591 | 602 | 590 | 604 | 591 | 615 | 597 | 592 | 584 |
| | 69.5 | 615 | 597 | 651 | 617 | 619 | 599 | 599 | 588 | 597 | 587 | 610 | 594 | 586 | 581 |
| | 80.5 | 603 | 590 | 641 | 611 | 603 | 590 | 598 | 586 | 600 | 589 | 615 | 597 | 592 | 584 |
| | 90.0 | 609 | 594 | 621 | 600 | 612 | 595 | 595 | 586 | 589 | 583 | 560 | 566 | 583 | 579 |
| | 99.7 | 588 | 582 | 620 | 600 | 601 | 589 | 600 | 589 | 599 | 588 | 570 | 572 | 596 | 586 |
| 2C | .1 | 459 | 510 | 462 | 512 | 429 | 494 | 442 | 501 | 444 | 502 | - | - | 431 | 495 |
| | 9.8 | 617 | 598 | 630 | 605 | 608 | 593 | 596 | 586 | 598 | 588 | - | - | 604 | 591 |
| | 19.8 | 588 | 582 | 597 | 587 | 591 | 584 | 596 | 586 | 568 | 571 | - | - | 594 | 585 |
| | 30.4 | 602 | 590 | 598 | 588 | 590 | 583 | 593 | 585 | 537 | 554 | - | - | 603 | 590 |
| | 38.4 | 623 | 601 | 614 | 596 | 607 | 593 | 589 | 583 | 607 | 593 | - | - | 608 | 593 |
| | 42.8 | | | | | F - A - I - | | L - E - D | | | | | | | |

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## APPENDIX IV

### BEARING/OIL IN AND OIL OUT TEMPERATURE DATA

| | | DRIVE BEARING | | | | | | LOAD BEARING | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | OIL IN | | OIL OUT | | O.R. | | OIL IN | | OIL OUT | | I. R. | | O.R. | |
| TEST NO. | TIME HRS. | °F | °R | °F | °R | °F | °R | °F | °R | °F | °R | °F | °R | °F | °R |
| 3A Humble FN-3158 | .1 | 382 | 468 | 408 | 482 | 378 | 465 | 374 | 463 | 390 | 472 | 390 | 472 | 374 | 463 |
| | 10.1 | 610 | 594 | 615 | 597 | 607 | 593 | 594 | 585 | 599 | 588 | 610 | 594 | 595 | 586 |
| | 20.0 | 594 | 585 | 611 | 595 | 600 | 589 | 595 | 586 | 598 | 588 | 610 | 594 | 592 | 584 |
| | 30.0 | 583 | 579 | 602 | 590 | 591 | 584 | 591 | 594 | 594 | 585 | 610 | 594 | 592 | 584 |
| | 40.0 | 587 | 581 | 608 | 593 | 594 | 585 | 600 | 589 | 600 | 589 | 610 | 594 | 596 | 586 |
| | 50.0 | 586 | 581 | 606 | 592 | 594 | 585 | 600 | 589 | 605 | 591 | 615 | 597 | 600 | 589 |
| | 60.0 | 594 | 585 | 590 | 583 | 594 | 585 | 596 | 586 | 577 | 576 | 560 | 566 | 594 | 585 |
| | 69.9 | 598 | 588 | 603 | 590 | 601 | 589 | 592 | 584 | 573 | 574 | 570 | 572 | 599 | 588 |
| | 71.7 | | | | | F - A - I - | | L - E - D | | | | | | | |
| 3B | .1 | 427 | 493 | 426 | 492 | 426 | 492 | 397 | 476 | 404 | 480 | 445 | 503 | 399 | 477 |
| | 10.1 | 620 | 600 | 588 | 582 | 613 | 596 | 600 | 589 | 577 | 576 | 590 | 583 | 598 | 588 |
| | 20.1 | 600 | 589 | 589 | 583 | 602 | 590 | 582 | 579 | 582 | 579 | 590 | 583 | 597 | 587 |
| | 30.0 | 595 | 586 | 584 | 580 | 584 | 580 | 591 | 584 | 586 | 581 | 610 | 594 | 598 | 588 |
| | 40.0 | 608 | 593 | 588 | 582 | 615 | 597 | 588 | 582 | 580 | 578 | 615 | 597 | 595 | 586 |
| | 40.3 | | | | | F - A - I - | | L - E - D | | | | | | | |
| 3C | .8 | 590 | 583 | 646 | 614 | 615 | 597 | 613 | 596 | 602 | 590 | - | - | 616 | 598 |
| | 9.9 | 626 | 603 | 649 | 616 | 599 | 588 | 608 | 593 | 597 | 587 | - | - | 613 | 596 |
| | 20.2 | 595 | 586 | 621 | 600 | 550 | 561 | 584 | 580 | 560 | 566 | - | - | 597 | 587 |
| | 33.6 | 600 | 589 | 626 | 603 | 551 | 561 | 588 | 582 | 564 | 569 | - | - | 608 | 593 |
| | 40.9 | 610 | 594 | 632 | 606 | 548 | 560 | 583 | 579 | 563 | 568 | - | - | 601 | 589 |
| | 49.3 | 600 | 589 | 623 | 601 | 562 | 568 | 575 | 575 | 557 | 565 | - | - | 591 | 584 |
| 4A Humble FN-3158 plus 10% Kendall Resin | .1 | 466 | 514 | 454 | 508 | 463 | 513 | 443 | 501 | 413 | 485 | 475 | 519 | 439 | 499 |
| | 10.0 | 599 | 588 | 617 | 598 | 601 | 589 | 592 | 584 | 569 | 571 | 580 | 578 | 591 | 584 |
| | 21.5 | 613 | 596 | 635 | 608 | 616 | 598 | 594 | 585 | 562 | 568 | 500 | 533 | 602 | 590 |
| | 30.5 | 594 | 585 | 618 | 599 | 597 | 587 | 584 | 580 | 549 | 560 | 555 | 564 | 592 | 584 |
| | 44.0 | 519 | 544 | 544 | 558 | 514 | 541 | 480 | 522 | 430 | 495 | 510 | 539 | 480 | 522 |
| | 51.0 | 579 | 577 | 591 | 584 | 591 | 584 | 574 | 574 | 559 | 566 | 585 | 580 | 589 | 583 |
| | 58.0 | 591 | 584 | 606 | 592 | 599 | 588 | 588 | 582 | 563 | 568 | 585 | 580 | 598 | 588 |
| | 71.0 | 584 | 580 | 603 | 590 | 593 | 585 | 571 | 573 | 543 | 557 | 560 | 566 | 585 | 580 |
| | 80.1 | 599 | 588 | 617 | 598 | 606 | 592 | 575 | 575 | 547 | 559 | 555 | 564 | 591 | 584 |
| | 90.5 | 606 | 592 | 623 | 601 | 602 | 590 | 583 | 579 | 561 | 567 | 490 | 528 | 586 | 581 |
| | 99.0 | 603 | 590 | 623 | 601 | 600 | 589 | 582 | 579 | 558 | 565 | 495 | 530 | 586 | 581 |
| 4B | 0.8 | 616 | 598 | 618 | 599 | 613 | 596 | 580 | 578 | 563 | 568 | 465 | 514 | 582 | 579 |
| | 10.7 | 598 | 588 | 612 | 595 | 602 | 590 | 594 | 585 | 586 | 581 | 590 | 583 | 595 | 586 |
| | 21.0 | 615 | 597 | 631 | 606 | 616 | 598 | 619 | 599 | 604 | 591 | 585 | 580 | 616 | 598 |
| | 30.4 | 580 | 578 | 598 | 588 | 591 | 584 | 582 | 579 | 595 | 586 | 560 | 566 | 590 | 583 |
| | 40.0 | 581 | 578 | 600 | 589 | 587 | 581 | 587 | 581 | 594 | 585 | 525 | 547 | 591 | 584 |
| | 50.0 | 585 | 580 | 600 | 589 | 594 | 585 | 593 | 585 | 599 | 588 | 540 | 555 | 600 | 589 |

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APPENDIX IV

BEARING/OIL IN AND OIL OUT TEMPERATURE DATA

| TEST NO. | TIME HRS. | DRIVE BEARING OIL IN °F | °R | OIL OUT °F | °R | O. R. °F | °R | LOAD BEARING OIL IN °F | °R | OIL OUT °F | °R | I.R. °F | °R | O.R. °F | °R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4B (Continued) | 59.7 | 589 | 583 | 603 | 590 | 598 | 588 | 588 | 582 | 595 | 586 | 530 | 550 | 596 | 586 |
| | 70.1 | 589 | 583 | 605 | 591 | 598 | 588 | 598 | 588 | 604 | 591 | 535 | 553 | 603 | 590 |
| | 84.0 | 596 | 586 | 610 | 594 | 604 | 591 | 595 | 586 | 601 | 589 | 530 | 550 | 601 | 589 |
| | 90.0 | 595 | 586 | 611 | 595 | 604 | 591 | 599 | 588 | 604 | 591 | 535 | 553 | 606 | 592 |
| | 99.0 | 598 | 588 | 612 | 595 | 605 | 591 | 593 | 585 | 601 | 589 | 525 | 547 | 601 | 589 |
| 4C Humble FN-3158 plus 10% Kendall Resin | 0.4 | 544 | 558 | 565 | 569 | 522 | 545 | 519 | 544 | 503 | 535 | - | - | 525 | 547 |
| | 10.1 | 618 | 599 | 645 | 614 | 574 | 574 | 595 | 586 | 576 | 575 | - | - | 605 | 591 |
| | 22.9 | 627 | 604 | 656 | 620 | 579 | 577 | 599 | 588 | 582 | 579 | - | - | - | - |
| | 29.8 | 595 | 586 | 625 | 603 | 555 | 564 | 591 | 584 | 580 | 578 | - | - | 600 | 589 |
| | 40.3 | 595 | 586 | 624 | 602 | 574 | 574 | 589 | 583 | 593 | 585 | - | - | 598 | 587 |
| | 48.2 | 596 | 586 | 625 | 603 | 574 | 574 | 594 | 585 | 596 | 586 | - | - | 602 | 590 |
| 5A Dow Corning XF-1-0301 | 0.3 | 417 | 487 | 518 | 543 | 510 | 539 | 498 | 532 | 498 | 532 | - | - | 482 | 523 |
| | 10.0 | 605 | 591 | 618 | 599 | 607 | 593 | 589 | 583 | 591 | 584 | - | - | 595 | 586 |
| | 20.0 | 604 | 591 | 614 | 596 | 607 | 593 | 589 | 583 | 590 | 583 | - | - | 594 | 585 |
| | 29.1 | 597 | 587 | 608 | 593 | 603 | 590 | 585 | 580 | 565 | 569 | - | - | 600 | 589 |
| | 43.0 | 589 | 583 | 601 | 589 | 596 | 586 | 583 | 579 | 564 | 569 | - | - | 600 | 589 |
| | 50.1 | 579 | 577 | 594 | 585 | 590 | 583 | 579 | 577 | 558 | 565 | - | - | 598 | 588 |
| | 58.4 | 595 | 586 | 609 | 594 | 602 | 590 | 602 | 590 | 560 | 566 | - | - | 601 | 589 |
| | 70.0 | 599 | 588 | 609 | 594 | 606 | 592 | 577 | 576 | 551 | 561 | - | - | 592 | 584 |
| | 80.4 | 605 | 591 | 618 | 599 | 613 | 596 | 587 | 581 | 564 | 569 | - | - | 599 | 588 |
| | 90.0 | 592 | 584 | 607 | 593 | 604 | 591 | 589 | 583 | 569 | 571 | - | - | 603 | 590 |
| | 99.0 | 595 | 586 | 607 | 593 | 606 | 592 | 595 | 586 | 573 | 574 | - | - | 607 | 593 |
| 5B | 0.1 | - | - | 457 | 509 | 451 | 506 | 427 | 493 | 435 | 497 | - | - | 408 | 482 |
| | 9.3 | 613 | 596 | 550 | 561 | 612 | 595 | 593 | 585 | 579 | 577 | - | - | 605 | 591 |
| | 23.0 | 621 | 600 | 554 | 558 | 616 | 598 | 592 | 584 | 544 | 558 | - | - | 600 | 589 |
| | 30.0 | 588 | 582 | 595 | 586 | 596 | 586 | 588 | 582 | 573 | 574 | - | - | 602 | 590 |
| | 38.5 | 610 | 594 | 618 | 599 | 607 | 593 | 575 | 575 | 576 | 575 | - | - | 590 | 583 |
| | 50.0 | 608 | 593 | 604 | 591 | 607 | 593 | 598 | 588 | 576 | 575 | - | - | 608 | 593 |
| | 60.7 | 615 | 597 | 600 | 589 | 613 | 596 | 601 | 589 | 578 | 576 | - | - | 610 | 594 |
| | 71.1 | 606 | 592 | 593 | 585 | 607 | 593 | 595 | 586 | 570 | 572 | - | - | 604 | 591 |
| | 80.6 | 608 | 593 | 595 | 586 | 609 | 594 | 597 | 587 | 568 | 571 | - | - | 605 | 591 |
| | 93.6 | 605 | 591 | 608 | 593 | 599 | 588 | 579 | 577 | 571 | 573 | - | - | 580 | 578 |
| | 99.0 | 610 | 594 | 617 | 598 | 606 | 592 | 595 | 586 | 602 | 590 | - | - | 600 | 589 |
| 5C | 0.1 | 451 | 506 | 459 | 510 | 420 | 489 | 433 | 496 | 415 | 486 | - | - | 450 | 505 |
| | 9.6 | 631 | 606 | 652 | 618 | 594 | 585 | 584 | 580 | 558 | 565 | - | - | 596 | 586 |
| | 20.7 | 628 | 604 | 648 | 615 | 596 | 586 | 583 | 579 | 558 | 565 | - | - | 594 | 585 |
| | 30.8 | 613 | 596 | 637 | 609 | 589 | 583 | 578 | 576 | 563 | 568 | - | - | 588 | 582 |
| | 40.3 | 620 | 600 | 642 | 612 | 594 | 585 | 606 | 592 | 575 | 575 | - | - | 612 | 595 |
| | 49.3 | 615 | 597 | 637 | 609 | 591 | 584 | 596 | 586 | 571 | 573 | - | - | 605 | 591 |

APPENDIX IV

BEARING/OIL IN AND OIL OUT TEMPERATURE DATA

| TEST NO. | TIME HRS. | DRIVE BEARING OIL IN °F | °R | DRIVE BEARING OIL OUT °F | °R | DRIVE BEARING O.R. °F | °R | LOAD BEARING OIL IN °F | °R | LOAD BEARING OIL OUT °F | °R | LOAD BEARING I.R. °F | °R | LOAD BEARING O.R. °F | °R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6A | | | | | | | | | | | | | | | |
| Mobil XRM-109F plus | 0.2 | 574 | 574 | 578 | 576 | 561 | 567 | 548 | 560 | 547 | 559 | 520 | 544 | 536 | 553 |
| 10% Kendall Resin | 10.5 | 595 | 586 | 597 | 587 | 595 | 586 | 589 | 583 | 594 | 585 | 530 | 550 | 582 | 579 |
| | 20.0 | 603 | 590 | 596 | 586 | 599 | 588 | 594 | 585 | 600 | 589 | 525 | 547 | 594 | 585 |
| | 30.5 | 603 | 590 | 596 | 586 | 601 | 589 | 597 | 587 | 600 | 589 | 535 | 553 | 595 | 585 |
| | 42.5 | 601 | 589 | 585 | 580 | 597 | 587 | 595 | 586 | 598 | 588 | 533 | 551 | 594 | 585 |
| | 51.2 | 602 | 590 | 583 | 579 | 596 | 586 | 596 | 586 | 598 | 588 | 540 | 555 | 589 | 583 |
| | 58.8 | 597 | 587 | 585 | 580 | 592 | 584 | 592 | 584 | 596 | 586 | 540 | 555 | 589 | 583 |
| | 70.0 | 602 | 590 | 593 | 585 | 598 | 588 | 594 | 585 | 599 | 588 | 530 | 550 | 591 | 584 |
| | 80.6 | 602 | 590 | 586 | 581 | 599 | 588 | 595 | 586 | 598 | 588 | 535 | 553 | 589 | 583 |
| | 90.9 | 606 | 592 | 611 | 595 | 597 | 587 | 607 | 593 | 614 | 596 | 540 | 555 | 585 | 580 |
| | 99.0 | 611 | 595 | 618 | 599 | 608 | 593 | 613 | 596 | 621 | 600 | 590 | 583 | 602 | 590 |
| 6B | | | | | | | | | | | | | | | |
| | .2 | 612 | 595 | 614 | 596 | 593 | 585 | 573 | 574 | 569 | 571 | 610 | 594 | 542 | 556 |
| | 10.4 | 610 | 594 | 623 | 601 | 510 | 594 | 592 | 584 | 595 | 586 | 605 | 591 | 585 | 580 |
| | 22.2 | 618 | 599 | 623 | 601 | 611 | 595 | 592 | 584 | 596 | 586 | 620 | 600 | 583 | 579 |
| | 33.0 | 606 | 592 | 614 | 596 | 601 | 589 | 593 | 585 | 592 | 584 | 570 | 572 | 575 | 573 |
| | 44.4 | 644 | 613 | 653 | 618 | 625 | 603 | 599 | 588 | 592 | 584 | 650 | 616 | 569 | 571 |
| | 50.0 | 615 | 597 | 635 | 608 | 608 | 593 | 596 | 586 | 603 | 590 | 610 | 594 | 584 | 580 |
| | 57.7 | 630 | 605 | 644 | 613 | 612 | 595 | 603 | 590 | 607 | 593 | 625 | 603 | 580 | 578 |
| | 70.0 | 616 | 598 | 633 | 607 | 604 | 591 | 594 | 585 | 601 | 589 | 620 | 600 | 580 | 578 |
| | 80.8 | 620 | 600 | 637 | 609 | 610 | 594 | 599 | 588 | 606 | 592 | 640 | 611 | 686 | 580 |
| | 90.2 | 621 | 600 | 638 | 610 | 611 | 595 | 601 | 589 | 606 | 592 | 635 | 608 | 585 | 580 |
| | 100.0 | 623 | 601 | 639 | 610 | 613 | 596 | 601 | 589 | 605 | 591 | 630 | 605 | 687 | 637 |
| 6C | | | | | | | | | | | | | | | |
| | 1.0 | 622 | 601 | 648 | 615 | 599 | 588 | - | - | 613 | 596 | - | - | 598 | 588 |
| | 10.1 | 612 | 595 | 638 | 610 | 590 | 583 | - | - | 608 | 593 | - | - | 596 | 586 |
| | 20.0 | 611 | 595 | 636 | 609 | 587 | 581 | - | - | 596 | 586 | - | - | 593 | 585 |
| | 30.6 | 615 | 597 | 640 | 611 | 591 | 584 | - | - | 599 | 588 | - | - | 594 | 585 |
| | 42.0 | 610 | 594 | 634 | 608 | 588 | 582 | - | - | 596 | 586 | - | - | 593 | 585 |
| | 49.7 | 611 | 595 | 636 | 609 | 590 | 583 | - | - | 599 | 588 | - | - | 602 | 590 |
| 7A | | | | | | | | | | | | | | | |
| Esso AL07873 | 0.2 | 403 | 479 | 490 | 528 | 486 | 525 | 460 | 511 | 455 | 508 | 475 | 519 | 459 | 510 |
| | 10.0 | 586 | 581 | 599 | 588 | 585 | 580 | 573 | 574 | 579 | 577 | 600 | 589 | 570 | 572 |
| | 21.0 | 578 | 576 | 595 | 586 | 587 | 581 | 588 | 582 | 594 | 585 | 575 | 575 | 590 | 583 |
| | 30.2 | 585 | 580 | 597 | 587 | 593 | 585 | 601 | 589 | 606 | 592 | 560 | 566 | 601 | 589 |
| | 44.9 | 585 | 580 | 594 | 585 | 591 | 584 | 596 | 586 | 602 | 590 | 575 | 575 | 597 | 587 |
| | 50.0 | 592 | 584 | 602 | 590 | 594 | 585 | 596 | 586 | 602 | 590 | 570 | 572 | 591 | 584 |
| | 59.2 | 593 | 585 | 560 | 589 | 595 | 586 | 596 | 586 | 601 | 589 | 560 | 566 | 592 | 584 |
| | 70.0 | 600 | 589 | 608 | 593 | 602 | 590 | 597 | 587 | 603 | 590 | 510 | 539 | 596 | 586 |
| | 80.3 | 590 | 583 | 599 | 588 | 599 | 588 | 596 | 586 | 592 | 584 | 510 | 539 | 597 | 587 |
| | 91.0 | 571 | 573 | 565 | 569 | 563 | 568 | 553 | 563 | 550 | 561 | 545 | 558 | 542 | 556 |
| | 99.2 | 604 | 591 | 611 | 595 | 609 | 594 | 603 | 590 | 607 | 593 | 560 | 566 | 604 | 591 |

## BEARING/OIL IN AND OIL OUT TEMPERATURE DATA

| TEST NO. | TIME HRS. | DRIVE BEARING OIL IN °F | DRIVE BEARING OIL IN °R | DRIVE BEARING OIL OUT °F | DRIVE BEARING OIL OUT °R | DRIVE BEARING O.R. °F | DRIVE BEARING O.R. °R | LOAD BEARING OIL IN °F | LOAD BEARING OIL IN °R | LOAD BEARING OIL OUT °F | LOAD BEARING OIL OUT °R | LOAD BEARING I.R. °F | LOAD BEARING I.R. °R | LOAD BEARING O.R. °F | LOAD BEARING O.R. °R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7B | 0.2 | 420 | 489 | 422 | 490 | 419 | 488 | 429 | 494 | 433 | 496 | 500 | 533 | 400 | 478 |
| | 10.5 | 606 | 592 | 611 | 595 | 604 | 591 | 616 | 598 | 620 | 600 | 625 | 603 | 603 | 590 |
| | 22.0 | 599 | 588 | 603 | 590 | 597 | 587 | 610 | 594 | 615 | 597 | 640 | 611 | 597 | 587 |
| | 30.5 | 599 | 588 | 605 | 591 | 595 | 586 | 614 | 596 | 619 | 599 | 620 | 600 | 600 | 589 |
| | 37.5 | 601 | 589 | 606 | 592 | 598 | 588 | 615 | 597 | 619 | 599 | 635 | 608 | 601 | 589 |
| | 49.9 | 603 | 590 | 608 | 593 | 600 | 589 | 618 | 599 | 621 | 600 | 625 | 603 | 603 | 590 |
| | 60.0 | 601 | 589 | 605 | 591 | 599 | 588 | 620 | 600 | 622 | 601 | 625 | 603 | 607 | 593 |
| | 70.0 | 613 | 596 | 621 | 600 | 611 | 595 | 610 | 594 | 610 | 594 | 610 | 594 | 599 | 588 |
| | 80.3 | 593 | 585 | 596 | 586 | 591 | 584 | 607 | 593 | 606 | 592 | 610 | 594 | 599 | 588 |
| | 91.0 | 596 | 586 | 598 | 588 | 591 | 584 | 602 | 590 | 601 | 589 | 615 | 597 | 587 | 581 |
| | 98.6 | 602 | 590 | 604 | 591 | 599 | 588 | 612 | 595 | 607 | 593 | 600 | 589 | 605 | 591 |
| 7C | 0.8 | 610 | 594 | 621 | 599 | 599 | 587 | 584 | 579 | 577 | 575 | - | - | 598 | 587 |
| | 10.3 | 588 | 582 | 599 | 587 | 580 | 577 | 581 | 577 | 578 | 575 | - | - | 591 | 583 |
| | 20.2 | 464 | 513 | 467 | 514 | 447 | 503 | 437 | 497 | 416 | 485 | - | - | 464 | 512 |
| | 30.5 | 613 | 596 | 619 | 598 | 597 | 586 | 606 | 591 | 595 | 585 | - | - | 613 | 596 |
| | 40.4 | 617 | 598 | 625 | 601 | 603 | 589 | 600 | 598 | 591 | 583 | - | - | 607 | 592 |
| | 48.8 | 614 | 596 | 625 | 601 | 598 | 587 | 600 | 598 | 593 | 584 | - | - | 610 | 593 |
| 8C DuPont Krytox 143 AB | 0.4 | 585 | 580 | 594 | 584 | 543 | 556 | 587 | 580 | 662 | 622 | - | - | 640 | 610 |
| | 10.1 | 620 | 600 | 615 | 596 | 546 | 558 | 606 | 591 | 652 | 616 | - | - | 620 | 599 |
| | 21.3 | 604 | 590 | 606 | 591 | 503 | 534 | 579 | 576 | 637 | 608 | - | - | 607 | 592 |
| | 30.9 | 615 | 596 | 615 | 596 | 565 | 568 | 590 | 582 | 634 | 606 | - | - | 606 | 591 |
| | 37.2 | 618 | 598 | 619 | 598 | 568 | 570 | 591 | 583 | 638 | 609 | - | - | 608 | 592 |
| | 49.0 | 611 | 594 | 611 | 594 | 563 | 567 | 584 | 579 | 629 | 604 | - | - | 601 | 588 |

# APPENDIX V

## TEST RIG POWER CONSUMPTION DATA

### 1. Mobil XRM-109F, (Test 1C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 6.55 | 227 | 42 | 9530 |
| 10.05 | 227 | 42 | 9530 |
| 22.85 | 227 | 42 | 9530 |
| 29.75 | 227 | 41 | 9300 |
| 40.85 | 227 | 42 | 9530 |
| 49.85 | 227 | 41 | 9300 |

### 2. Monsanto MCS-2931, (Test 2C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 2.3 | 228 | 42 | 9570 |
| 9.85 | 228 | 42 | 9570 |
| 21.35 | 228 | 42 | 9570 |
| 30.35 | 230 | 42 | 9655 |
| 36.45 | 230 | 42 | 9655 |
| 40.80 | failed | | |

### 3. Humble FN-3158, (Test 3C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 2.15 | 229 | 41 | 9390 |
| 9.95 | 229 | 39 | 8930 |
| 20.25 | 228 | 42 | 9570 |
| 36.05 | 228 | 42 | 9570 |
| 42.85 | 227 | 42 | 9530 |
| 48.35 | 227 | 42 | 9530 |

### 4. Humble FN-3158 plus 10% Kendall Resin, (Test 4C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 0.7 | 230 | 42 | 9660 |
| 10.1 | 227 | 41 | 9300 |
| 23.4 | 230 | 42 | 9660 |
| 30.5 | 228 | 43 | 9800 |
| 40.4 | 227 | 44 | 9980 |
| 48.2 | 227 | 44 | 9980 |

APPENDIX V (Continued)

5. Dow Corning XF-1-0301, (Test 5C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 0.4 | 230 | 40 | 9200 |
| 11.0 | 230 | 40 | 9200 |
| 21.4 | 230 | 42 | 9660 |
| 30.8 | 230 | 40 | 9200 |
| 40.2 | 230 | 42 | 9660 |
| 49.3 | 230 | 42 | 9660 |

6. Mobil XRM-109F plus 10% Kendall Resin, (Test 6C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 0.9 | 232 | 44 | 10200 |
| 10.1 | 232 | 44 | 10200 |
| 20.6 | 230 | 44 | 9300 |
| 30.6 | 230 | 44 | 9300 |
| 44.6 | 230 | 44 | 9300 |
| 47.5 | 230 | 44 | 9300 |

7. Esso AL07873, (Test 7C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 0.9 | 232 | 38 | 8800 |
| 6.2 | 230 | 36 | 8260 |
| 33.6 | 231 | 37 | 8540 |
| 37.9 | 231 | 27 | 8540 |

8. DuPont Krytox 143AB, (Test 8C)

| HOURS | VOLTS | AMPHERES | WATTS |
|---|---|---|---|
| 4.55 | 228 | 50 | 11400 |
| 11.15 | 228 | 50 | 11400 |
| 21.65 | 228 | 50 | 11400 |
| 30.95 | 228 | 50 | 11400 |
| 35.85 | 228 | 50 | 11400 |
| 45.55 | 230 | 51 | 11730 |

APPENDIX VI

CONTRACT WORK STATEMENT

NAS3-11171

EXHIBIT "A"
HIGH TEMPERATURE LUBRICANT SCREENING TESTS

I. Scope of Work

The work to be performed shall consist of determining the lubricating ability and stability of a number of high temperature lubricant candidates for use in high speed advanced aircraft. Results of testing fluids in modified existing bearing rigs using optimized 25 mm bearings shall be used in guiding full-scale bearing and seal assembly studies.

II. Specific Requirements

The Contractor shall furnish the necessary personnel, facilities, services and materials and do all things necessary for, or incident to, the work described below:

Task I - Test Rig and Test Elements

A. Test Rig

1. The Contractor shall utilize two (2) contractor-owned bearing test rigs, previously used in work performed in NASA Contract NAS3-7912 and those rigs as specified in paragraph 2 of this Task I. One rig shall be capable of using 25 mm bore test bearings to be operated at outer ring temperatures to 700°F and speeds between 20,000 rpm and 45,000 rpm. The other rig will be a constant speed machine capable of operation at a speed of 43,700 rpm. Each rig shall be capable of testing with two bearings simultaneously. The rigs shall have the ability to operate in an inert atmosphere of nitrogen. The test rigs shall be capable of loading the bearings to thrust loads in the range 100 to 900 lbs.

2. Modifications to the two (2) test rigs specified in paragraph 1 of this Task I shall be made as follows:

   a. Shaft end seals, using a double circumferential design internally pressurized with nitrogen, shall be provided to replace the existing labyrinth seals. The Contractor shall limit the double circumferential design and fabrication to two independent seal assemblies. If either or both of these double circumferential seal assemblies fail, as determined by the Contractor, subject to the NASA Project Manager approval, then the original labyrinth seals shall be used for all testing.

   b. The rigs provided by the Contractor have a 300 to 400 cc/minute oil flow rate with a 25 to 100 cc/hour make-up rate. The Contractor shall determine and recommend the reduction

F-4186A R100

of the oil flow rate for these rigs in accordance with the current engine practice, subject to the NASA Project Manager's approval.

c. An infrared pyrometer shall be provided for monitoring the inner ring temperature of one bearing in the test rig. The Contractor shall limit the pyrometer installation and assembly fabrication to two (2) independent pyrometer assemblies. If either or both of these pyrometer assemblies fail as determined by the Contractor, subject to the NASA Project Manager approval, then the inner ring temperature shall not be monitored.

d. Thermocouples shall be inserted through the rig housing into the pump by-pass drains to measure the temperature of the lubricant just before entering the bearings.

e. A by-pass assembly for the existing sight glasses shall be provided to determine oil flow rate. The Contractor shall limit the by-pass assembly fabrication and installation to two (2) independent by-pass assembly arrangements. If either or both assembly arrangements should fail to provide more accurate oil flow rate measurements as determined by the Contractor, subject to the approval of the NASA Project Manager, then the existing assembly arrangement shall be utilized throughout all testing.

f. The Contractor shall provide for the monitoring and control of the oxygen content of the test assembly.

B. Bearings

The Contractor shall utilize the Government Furnished Property, 146 pcs. 7205 VAP Racis, Balls and Retainer, as provided under Article XV of the Schedule, for the fabrication of bearings necessary for this test program. The Contractor shall provide 20 polyimide cages for film measurements.

C. Test Lubricants

1. The following eight lubricant test fluids shall be provided for evaluation as described in Task II.B.

a. Mobile Oil Company XRM-109F (synthetic paraffinic hydrocarbon).

b. XRM-109F plus 10% super refined Kendall Resin (4500CS)

c. XRM-109F plus XRM-127B plus 10% super refined Kendall resin (4500CS) blended to have same viscosity as Mobil XRM-177F at 500°F.

d. Dow Corning XFL-0301 (modified fluorosilicone)

e. DuPont Company Krytox 143AB, furnished under Article XV of this contract.

f. Humble Oil Company FN-3158 (super refined mineral oil)

g. FN-3158 with 10% super refined Kendall resin (4500CS)

h. Monsanto Co. MCS-293 improved (modified polyphenylether MCS-642 or equivalent)

2. The fluid manufacturers available physical property data shall be obtained and furnished to NASA for the eight test lubricants or individual blend constituents as listed in paragraph C.1.a through h of Task I. If available, these data shall include the following properties:

a. Kinematic voscosity (at -40°, -20°, 0°, 100°, 210°, 400°, 500° and 600°F).

b. Acid number

c. Flash point (°F)

d. Fire point (°F)

e. Pour point (°F)

f. Density (0° to 600°F)

g. Specific heat (0° to 600°F)

h. Nitrogen solubility

i. Compatibility with possible system materials

j. Autogenous ignition temperature (°F)

k. Surface tension

l. Isoteniscope data

Task II - Lubricant Evaluation

The Contractor shall perform tests, conditions and procedures as described below, using the eight (8) lubricants listed in Task I, paragraph C.1.a. through h in the bearing test rigs to determine their relative lubricating abilities, extent of corrosion, system deposits, and modes of failure in the closed and inerted recirculating lubrication system.

EXHIBIT "A"

A. Test Conditions

1. Bearing outer ring temperature shall be maintained as close as possible to 600°F (± 15°F) using the modified test equipment described previously.

2. The temperature of the test lubricant supplied to the test bearings shall be allowed to stabliz e at a temperature such that the desired outer ring temperature can be maintained.

3. Inner ring (shaft) rotational speed shall be 43,700 ± 500 rpm to obtain a DN value of $1.1 \times 10^6$.

4. The Contractor shall determine and recommend, subject to the NASA Project Manager's approval, the thrust load to be used for all testing.

5. A positive nitrogen supply pressure shall be held to insure nitrogen flow into the test cavity.

6. Total oxygen content of the test cavity atmosphere shall not exceed 0.5 percent by volume, if the double circumferential seal assembly described in Task I, A.2.a, is used. If the original labyrinth seal assembly is used, the total oxygen content by volume shall not exceed 1.25%.

B. Test Procedures

The testing program shall consist of running each of the previously enumerated fluids except DuPont Krytox 143AB in the experimental rigs with two sets (2 bearings each set) of the 25 mm bearings at the test conditions, for a duration of 100 hours each bearing set or until failure is indicated by (a) a sudden rise in the bearing torque, temperature, or vibration (detected by vibra-switch), or (b) excessive coking of the lubricant to the extent that oil flow to bearings cannot be maintained. Prior to testing, the lubricants shall be degassed by subjecting them to pressure of $10^{-3}$ mm Mercury either for a 72-hour period at room temperature or at a temperature not exceeding 200°F for a period of at least 1 hour before running the tests. Careful atmosphere control shall be used during the tests to insure inerting. Nitrogen gas (99.9 percent by volume $N_2$) containing not more than 50 ppm oxygen and 5 ppm hydrocarbon (as Methane) and having a dew point of -90°F or lower shall be used as a cover gas. Only 4 new bearings shall be used for each lubricant tested and the number of rig assemblies shall be limited to a total of four for each lubricant. Any inner ring temperature measurements using the pyrometer assembly described in paragraph A.2.c. shall be made on one bearing with each lubricant. Testing shall terminate when these limits are reached.

In addition to the above tests, each of the eight fluids shall be tested in the experimental film measuring rig with one set (two bearings per set) of the 25 mm bearings using a polyimide cage at the test conditions, for a duration of 50 hours each bearing set or until failure as above defined. In the event the polyimide cage fails and the rest of the bearing is considered serviceable, as determined by the Contractor, the cage shall be replaced. Any change in film measurement testing recommended by the Contractor shall be subject to the NASA Project Manager's approval.

C. Data Required

1. After each test, the bearings and samples of system deposits shall be preserved. One deposit sample from each of no more than seven fluids shall be analyzed for carbon, hydrogen, oxygen, metals, nitrogen, fluorine, and silicon content. Photographs shall be provided for one-half of the bearings tested, as recommended by the Contractor, subject to the approval of the NASA Project Manager. One typical photograph of the test cavity and components shall be provided for each lubricant tested. One typical bearing tested in each fluid shall be cross-groove traced with a "taly-rond" instrument to detect geometry changes.

2. Periodic samples of the test lubricants shall be taken for analysis during one test with each lubricant. Sample size shall be 20 cc to obtain neutralization number, viscosity, and dirt content after 2, 10, 50, and 100 hours of operation. These parameters shall be determined for each sample.

3. The lubricant film thickness shall be measured by AC conductivity and capacitance techniques using an existing monitoring system developed under Task Orders III and V of NAS3-7912, incorporated herein by reference and hereby made a part hereof, in the variable speed film measuring test rig described previously. One of the six bearings tested with each of the seven fluids (other than Krytox) shall be monitored. The eighth fluid, DuPont Krytox 143AB, furnished under ARTICLE XV of this contract, shall be tested only for purposes of this film thickness determination using two bearings, one of which will be monitored.

   For all eight fluids, measurements shall be taken every ten hours during the life of the test bearing or until failure of the mating bearing. Continuous monitoring (manual data recording) shall be done during the first hour of operation, providing the test bearing or the mating bearing do not fail.

4. Oil temperature shall be monitored every six minutes, inner ring temperature shall be determined as previously specified, oxygen content shall be monitored every 10 hours and input motor power (on the variable speed rig only) shall be manually recorded every 10 hours.

D. Reporting Requirements

Reporting requirements shall be as described in the ARTICLE entitled "Reports of Work".

STANDARD FORM 30, JULY 1966
GENERAL SERVICES ADMINISTRATION
FED. PROC. REG. (41 CFR) 1-16.101

# AMENDMENT OF SOLICITATION/MODIFICATION OF CONTRACT

PAGE 1 OF 2

| 1. AMENDMENT/MODIFICATION NO. | 2. EFFECTIVE DATE | 3. REQUISITION/PURCHASE REQUEST NO. | 4. PROJECT NO. (If applicable) |
|---|---|---|---|
| 1 | | 397595 (Complete) | |

5. ISSUED BY CODE
NASA Lewis Research Center
Aeronautics Procurement Section, M.S. 77-3
21000 Brookpark Road
Cleveland, Ohio 44135

6. ADMINISTERED BY (If other than block 5) CODE

7. CONTRACTOR CODE FACILITY CODE
NAME AND ADDRESS
(Street, city, county, state, and ZIP Code)
SKF Industries, Inc.
Engineering & Research Center
1100 First Avenue
King of Prussia, Pennsylvania 19406

8.
☐ AMENDMENT OF SOLICITATION NO. ______,
DATED ______ (See block 9)
☒ MODIFICATION OF CONTRACT/ORDER NO. NAS3-11171
DATED 6-27-68 (See block 11)

9. THIS BLOCK APPLIES ONLY TO AMENDMENTS OF SOLICITATIONS

☐ The above numbered solicitation is amended as set forth in block 12. The hour and date specified for receipt of Offers ☐ is extended, ☐ is not extended.

Offerors must acknowledge receipt of this amendment prior to the hour and date specified in the solicitation, or as amended, by one of the following methods:

*(a) By signing and returning ______ copies of this amendment; (b) By acknowledging receipt of this amendment on each copy of the offer submitted; or (c) By separate letter or telegram which includes a reference to the solicitation and amendment numbers. FAILURE OF YOUR ACKOWLEDGMENT TO BE RECEIVED AT THE ISSUING OFFICE PRIOR TO THE HOUR AND DATE SPECIFIED MAY RESULT IN REJECTION OF YOUR OFFER. If, by virtue of this amendment you desire to change an offer already submitted, such change may be made by telegram or letter, provided such telegram or letter makes reference to the solicitation and this amendment, and is received prior to the opening hour and date specified.

10. ACCOUNTING AND APPROPRIATION DATA (If required)
Increased by $5,700.00 from $73,375.00 to $79,075.00
126-15-10-00-000-0-0-4-0251-1-Y-0N2637-54

11. THIS BLOCK APPLIES ONLY TO MODIFICATIONS OF CONTRACTS/ORDERS

(a) ☐ This Change Order is issued pursuant to ______
The Changes set forth in block 12 are made to the above numbered contract/order.

(b) ☐ The above numbered contract/order is modified to reflect the administrative changes (such as changes in paying office, appropriation data, etc.) set forth in block 12.

(c) ☒ This Supplemental Agreement is entered into pursuant to authority of "Changes" and "Limitation of Cost" Clauses of the Contract General Provisions and Mutual Agreement
It modifies the above numbered contract as set forth in block 12.

12. DESCRIPTION OF AMENDMENT/MODIFICATION

WHEREAS, the Government desires and the Contractor has concurred in a change in a Government-Furnished test lubricant specified in Exhibit "A"; and

WHEREAS, the Contractor has notified the Government that the estimates of cost and period of performance for the contract are anticipated to be in excess of the amounts specified in the SCHEDULE; and

WHEREAS, the Government desires to update the contract to reflect current estimates of cost and period of performance,

NOW THEREFORE, in consideration of the premises and of the obligations herein set forth, the Parties hereto do agree as follows:

1. On Page 2 of Exhibit "A" under Section C entitled "Test Lubricants" delete Item 1c. in its entirety and substitute in lieu thereof:

Except as provided herein, all terms and conditions of the document referenced in block 8, as heretofore changed, remain unchanged and in full force and effect.

13. ☐ CONTRACTOR/OFFEROR IS NOT REQUIRED TO SIGN THIS DOCUMENT ☒ CONTRACTOR/OFFEROR IS REQUIRED TO SIGN THIS DOCUMENT AND RETURN 3 COPIES TO ISSUING OFFICE

| 14. NAME OF CONTRACTOR/OFFEROR | | 17. UNITED STATES OF AMERICA | |
|---|---|---|---|
| BY ______ (Signature of person authorized to sign) | | BY ______ (Signature of Contracting Officer) | |
| 15. NAME AND TITLE OF SIGNER (Type or print) | 16. DATE SIGNED | 18. NAME OF CONTRACTING OFFICER (Type or print) John E. Hickey | 19. DATE SIGNED |

30-101

* U.S. GOVERNMENT PRINTING OFFICE : 1966 OF—255-145—(6-6)

"C. Esso ALO-7873 Turbo Oil (highly hindered ester)"

2. Delete ARTICLE II - PERIOD OF PERFORMANCE of the SCHEDULE in its entirety and substitute in lieu thereof:

"ARTICLE II - PERIOD OF PERFORMANCE

The estimated period of performance for the completion of the work set forth in ARTICLE I - STATEMENT OF WORK is fourteen (14) months from date of contract."

3. Delete ARTICLE X - ESTIMATED COST AND FIXED FEE of the SCHEDULE in entirety and substitute in lieu thereof:

"ARTICLE X - ESTIMATED COST AND FIXED FEE

The estimated cost of this contract is $74,945.00 exclusive of the fixed fee of $4,130.00. The total estimated cost and fixed fee is $79,075.00."

4. Under ARTICLE XV - GOVERNMENT FURNISHED PROPERTY an additional item will be furnished by the Government as follows:

"Thirteen and one-half ($13\frac{1}{2}$) gallons of Esso ALO-7873 Turbo Oil (highly hindered ester); within thirteen (13) months after contract award."

5. By virtue of this Modification No. 1, the estimated cost of the contract is revised as follows:

| | Estimated Cost | Fixed Fee | Total CPFF |
|---|---|---|---|
| Previous Contract Amount | $69,245.00 | $4,130.00 | $73,375.00 |
| This Modification No. 1 | 5,700.00 | -0- | 5,700.00 |
| Resultant Contract Amount | $74,945.00 | $4,130.00 | $79,075.00 |

6. As a result of this Supplemental Agreement No. 1 the fixed fee of this contract remains unchanged.

LIST OF REFERENCES

1. Allen, G. E., Peacock, L. A., and Rhoads, W. L., ,"Measurements of Lubricant Film Thickness in Hertzian Contacts", Supplemental Report of Task Order No. 5, SKF Report No. AL68T075, NASA Contract NAS3-7912., May 31, 1968.

2. Wachendofer, C. J., and Sibley, L. B., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures", Final Report on Contract NASW-492, National Aeronautics and Space Administration. Report No. CR-74097 (1965).

3. Peacock, L. A., and Rhoads, W. L., "Extreme Temperature Aerospace Bearing Lubrication Systems", Final Report on Task Order 5 of Contract NAS3-7912, National Aeronautics and Space Administration Report No. CR-72446 (1968).

4. Zaretsky, F. V., and Anderson, W. J., "Evaluation of High Temperature Bearing Cage Materials", NASA Technical Note D-3821 (January, 1966).

5. Hingley, C. G., Southerling, H. E., and Sibley, L. B., "Supersonic Transport Lubrication System Investigation" Semi-annual Progress Report No. 1 of Contract NAS3-6267, (1965).

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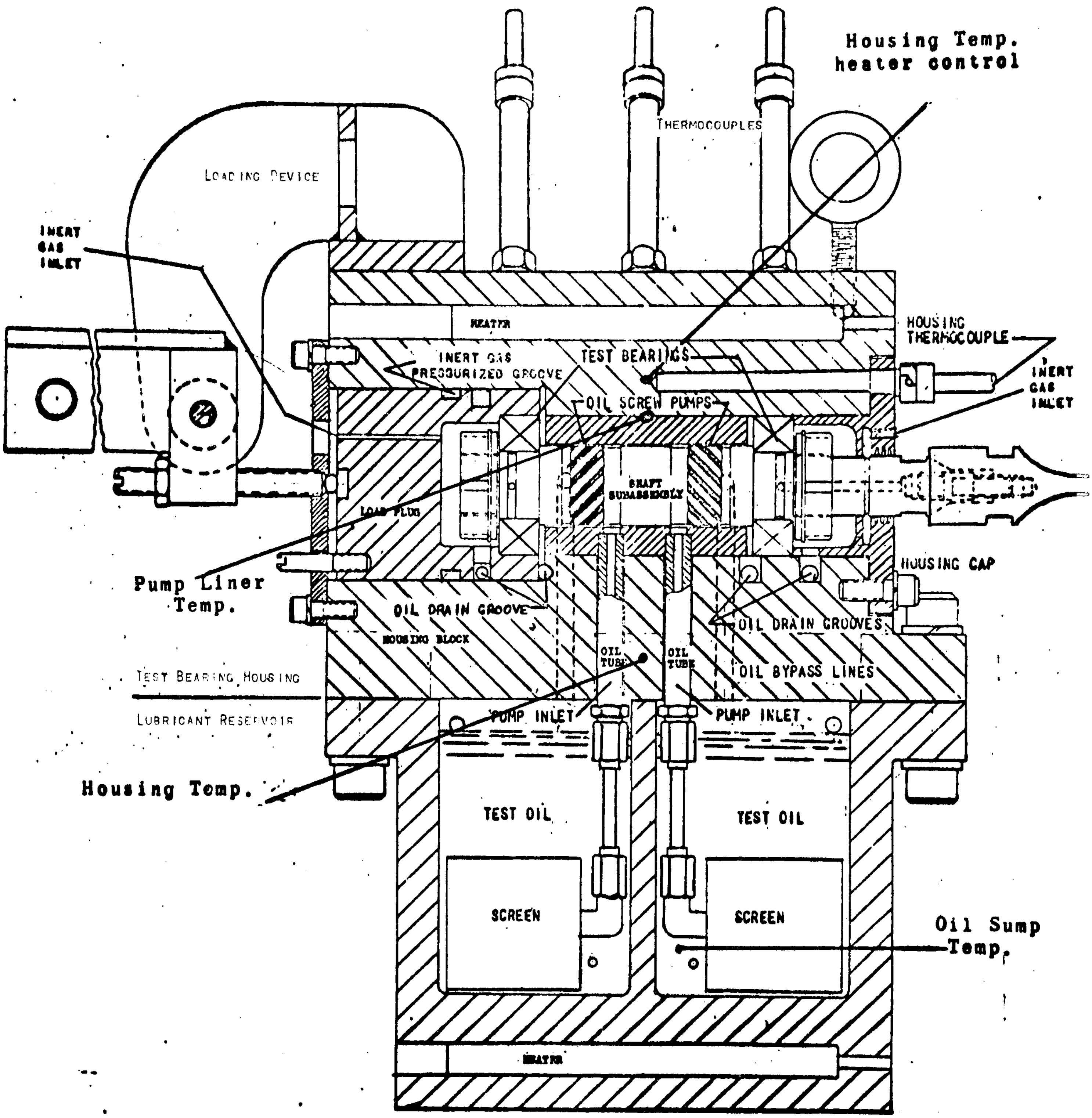
10. Martin, J. A., and Eberhardt, A. D., "Identification of Potential Failure Nuclei in Rolling Contact Fatigue," Journal of Basic Engineering, Trans. ASME, Series D Vol. 89, No. 4, Dec. 1967, p. 932.

11. Littman, W. E., Widner, R. L., Wolfe, J. O., and Stover, J. D., "The Role of Contact Lubrication in Propagation of Fatigue Cracks", ASME Transactions (Series F), Journal of Lubrication Technology, 90, 89 (1968).

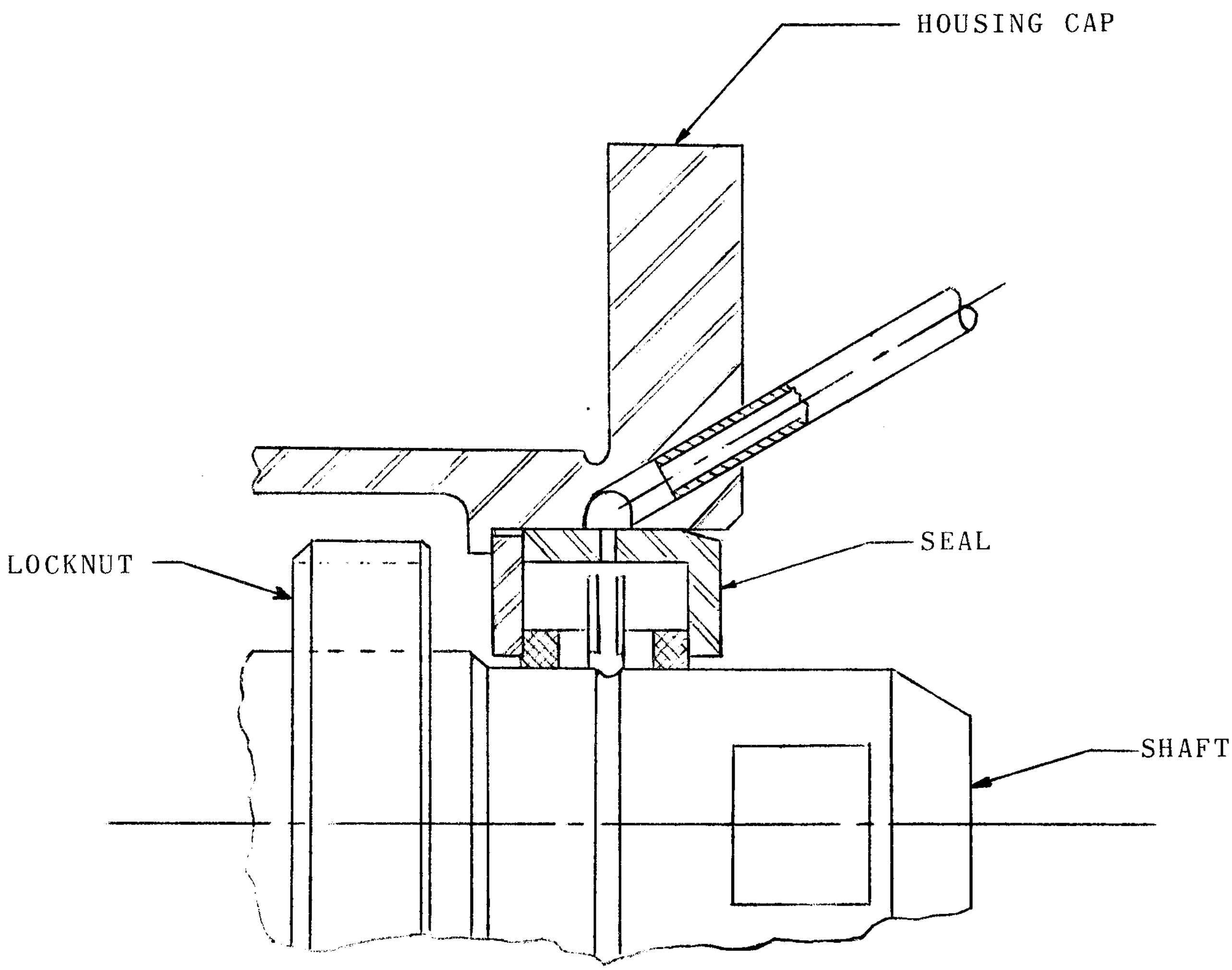
ENCLOSURE 1

LAYOUT SKETCH OF HIGH-SPEED HIGH-TEMPERATURE TEST RIG



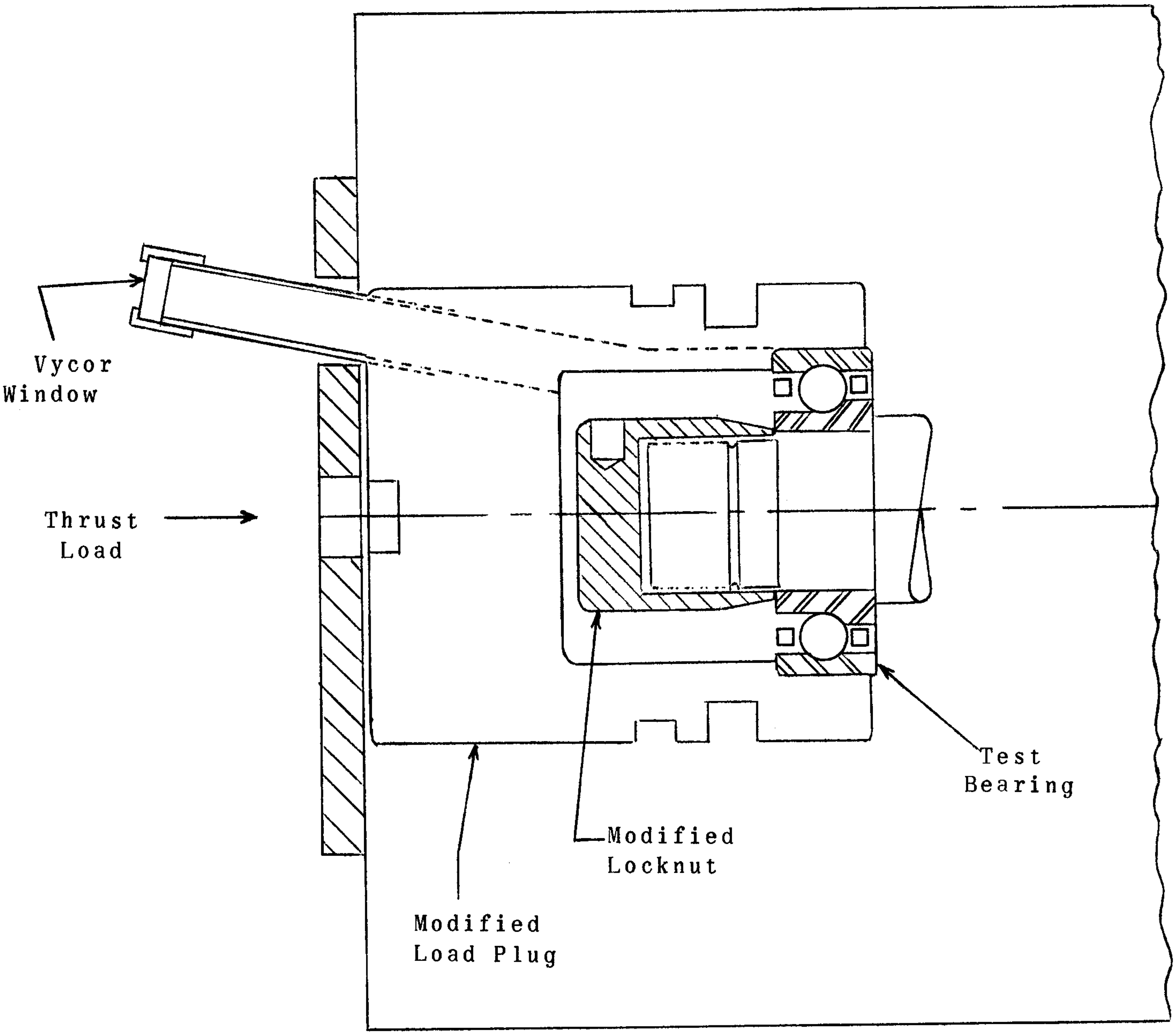
ENCLOSURE 2

SEAL ASSEMBLY



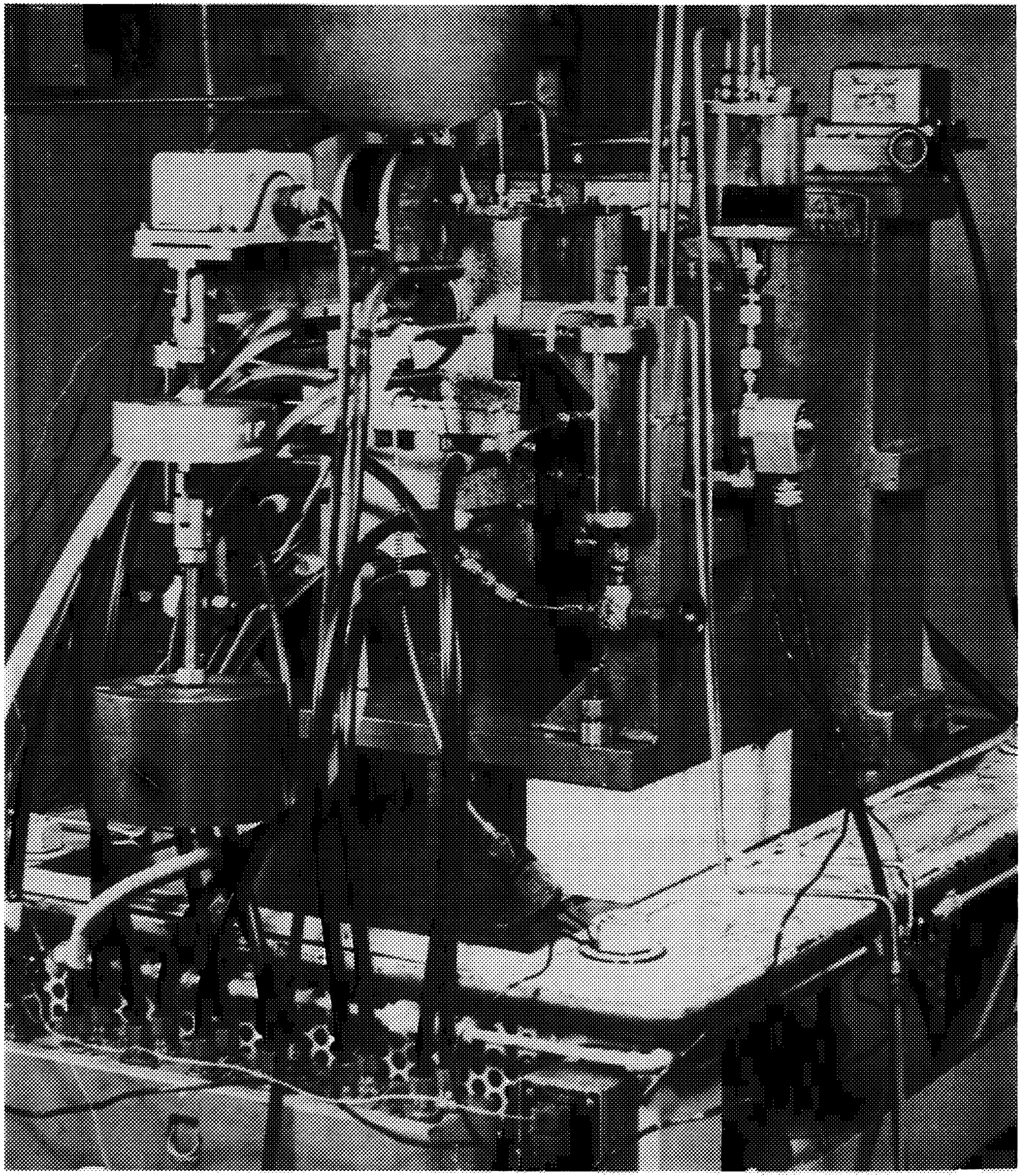
ENCLOSURE 3

PYROMETER VIEWING PORT ARRANGEMENT FOR INNER-RING TEMPERATURE MEASUREMENT



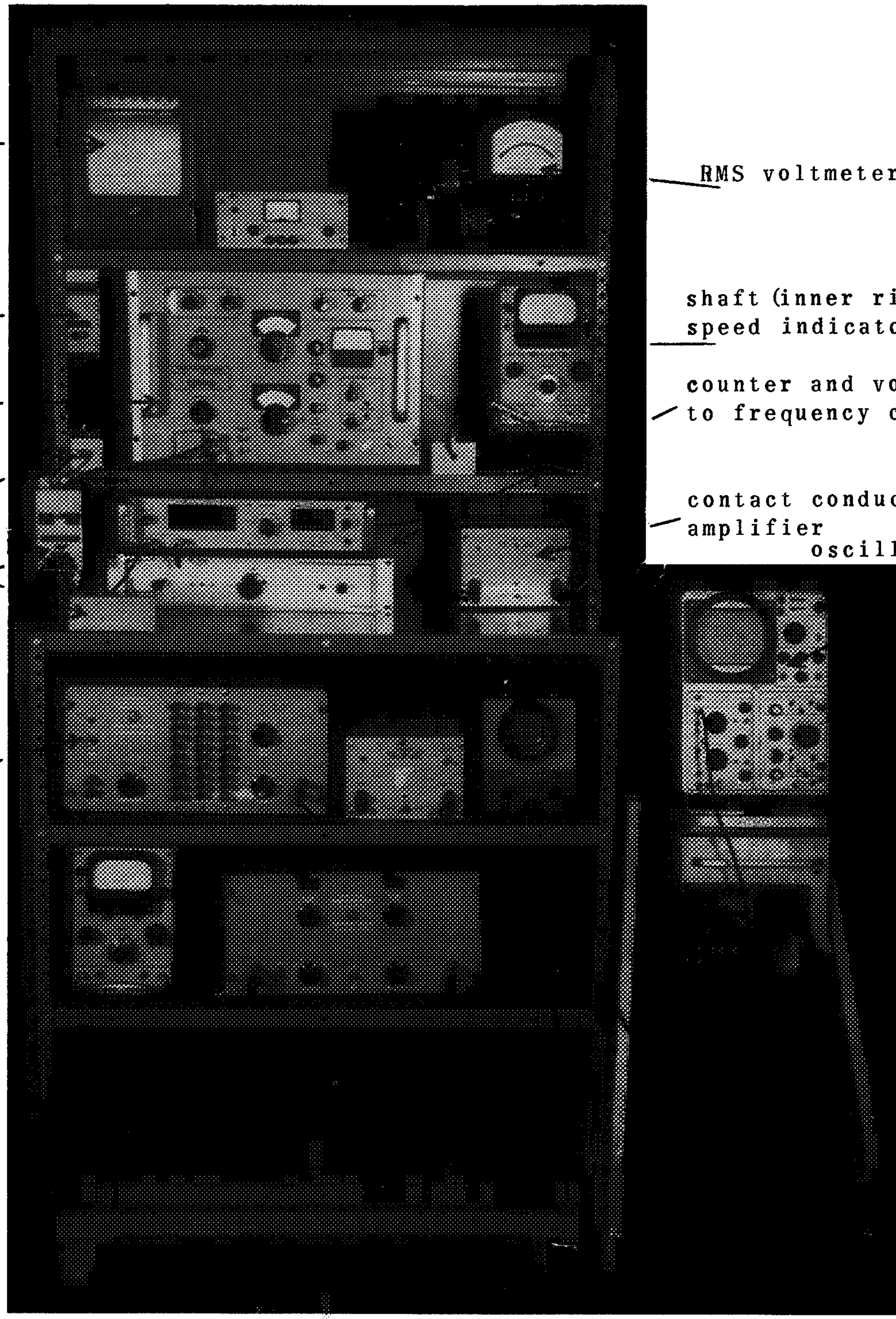
ENCLOSURE 4

HIGH-SPEED HIGH-TEMPERATURE BEARING TEST MACHINE



# ENCLOSURE 5

## FILM MEASURING INSTRUMENTATION



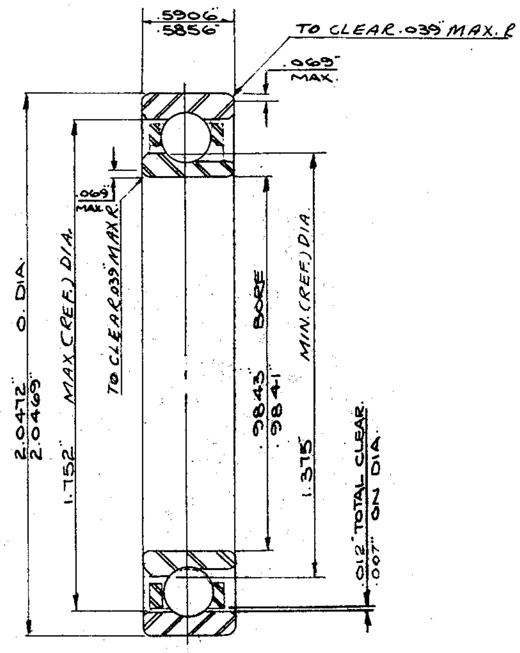

Note: Additional instrumentation comprises cage speed measuring system discussed in (1 ).

# ENCLOSURE 6

7205 VAP-3 TEST BEARING

| BEARING DATA | SKF |
|---|---|
| VENDOR'S PART № | 7205 VAP-3 |
| VENDOR'S DRAWING № | 7205 VAP-3 |
| BEARING TOLERANCE | ABEC5 |
| № & SIZE OF BALLS | 12-.3225" DIA. |
| INTERNAL RADIAL LOOSENESS (TOTAL) | .0020"-.0024" |
| TYPE OF BEARING | ANGULAR CONTACT |
| DESIGN CONTACT ANGLE | 22° |
| PITCH DIA. (NOMINAL) | 1.541 |
| CAGE WIDTH | .555" |

1. INNER AND OUTER RINGS TO BE MADE FROM M-50 STEEL, HARDNESS NOM. RC 62, RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENTIC GRAIN SIZE 7 MIN. PER SNYDER-GRAFF INTERCEPT METHOD.
2. BALLS TO BE MADE FROM M-50 STEEL HARDNESS NOM. RC 62, RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENTIC GRAIN SIZE 7 MIN. PER SNYDER-GRAFF INTERCEPT METHOD.
3. CAGE TO BE MADE FROM SILVER PLATED M-1 STEEL HARDNESS RC 55 MIN. ONE PIECE MACHINED, OUTER LAND RIDING.
4. GROOVE CONFORMITIES TO BE 52.3 % NOM. FOR INNER RING AND 52.3% NOM. FOR OUTER RING.
5. SHOULDER HEIGHTS TO BE 24.8-26.2 % FOR THE INNER RING AND 16.5-16.9 % FOR THE OUTER RING.
6. CROSS GROOVE SURFACE ROUGHNESS TO BE 4 MICRO-INCHES, RMS MAX. FOR BOTH INNER AND OUTER RINGS. SURFACE ROUGHNESS TO BE 1.2 MICRO-INCHES RMS MAX. FOR THE BALLS.




SKF INDUSTRIES, INC. PHILADELPHIA, PA.

BRG № 7205 VAP-3

| DRAWN | CHECK | APPR. | REG. |
|---|---|---|---|
| | | | DATE |
| SCALE | | | 7205 VAP-3 |

CUST.

RESEARCH LABORATORY SKF INDUSTRIES, INC.

ENCLOSURE 7

7205 VAP Test Bearing

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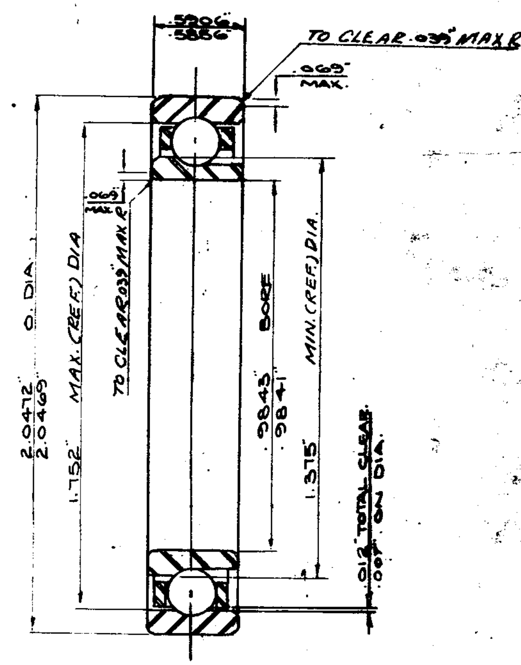
7205 VAP

| BEARING DATA | SKF |
|---|---|
| VENDOR'S PART № | 7205 VAP |
| VENDOR'S DRAWING № | 7205 VAP |
| BEARING TOLERANCE | ABEC5 |
| № & SIZE OF BALLS | 12-.3175" DIA. |
| INTERNAL RADIAL LOOSENESS (TOTAL) | .0020"-.0024" |
| TYPE OF BEARING | ANGULAR CONTACT |
| DESIGN CONTACT ANGLE | 24° |
| PITCH DIA. (NOMINAL) | 1.541 |
| CAGE WIDTH | .555" |




1. INNER AND OUTER RINGS TO BE MADE FROM M-50 STEEL, HARDNESS NOM. RC 62 , RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENTIC GRAIN SIZE 7 MIN. PER SNYDER - GRAFF INTERCEPT METHOD.
2. BALLS TO BE MADE FROM M-50 STEEL HARDNESS NOM. RC 62, RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENTIC GRAIN SIZE 7 MIN. PER SNYDER - GRAFF INTERCEPT METHOD.
3. CAGE TO BE MADE FROM SILVER PLATED M-1 STEEL HARDNESS RC 55 MIN. ONE PIECE MACHINED, OUTER LAND RIDING.
4. GROOVE CONFORMITIES TO BE 52.3 % NOM. FOR INNER RING AND 52.3% NOM. FOR OUTER RING
5. SHOULDER HEIGHTS TO BE 24.8 - 26.2 % FOR THE INNER RING AND 16.5 - 16.9 % FOR THE OUTER RING.
6. CROSS GROOVE SURFACE ROUGHNESS TO BE 4 MICRO-INCHES, RMS MAX. FOR BOTH INNER AND OUTER RINGS. SURFACE ROUGHNESS TO BE 1.2 MICRO-INCHES RMS MAX. FOR THE BALLS.
7 INNER AND OUTER RINGS TO BE BLACK OXIDE COATED PER AMS 2485

SKF INDUSTRIES, INC. PHILADELPHIA, PA.

BRG № 7205 VAP

| DRAWN | CHECK | APPR. | REG. |
|---|---|---|---|
| | | | DATE |
| SCALE | | 7205 VAP | |

ENCLOSURE 8

## COMPOSITION AND HOT HARDNESS CHARACTERISTICS OF HIGH-TEMPERATURE BEARING STEELS

| Elemental Composition, %: | M-50 |
|---|---|
| C | 0.77 - 0.85 |
| Mn | 0.35 max. |
| Si | 0.25 max. |
| Cr | 3.75 - 4.25 |
| P | 0.015 max. |
| S | 0.015 max. |
| Ni | 0.10 max. |
| Cu | 0.10 max. |
| Mo | 4.00 - 4.50 |
| W | 0.25 max. |
| V | 0.90 - 1.10 |
| Co | 0.25 max. |

| Hot Hardness After Long-Term Soaking at Temperature, Rc: | |
|---|---|
| Room Temp. | 64 |
| 400°F (431°K) | 61 |
| 600°F (589°K) | 57 |
| 800°F (700°K) | 55 |
| 1000°F (811°K) | 46 |

Hardness Measurements of Test Bearings, Rc:

| Bearing | Material | Inner Ring | Outer Ring | Balls |
|---|---|---|---|---|
| 7205 VAP | M-50 | 63.5 | 63.5 | 64.0 |
| 7205 VAP-3 | M-50 | 61.0 | 63.5 | 62.0 |

## ENCLOSURE 9

### DIMENSIONAL MEASUREMENTS DATA ON 7205 VAP AND VAP-3 BEARINGS BEFORE TESTING

| Bearing | No. | Groove Radii (mm) Inner | Outer | Contact Angle (degrees) | Radial Looseness (µm) | Bore (mm) | O.D. (mm) | Out of Roundness (µm) Inner | Outer | Taper (µm) Inner | Outer |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 884101 | 76 | 4.207 | 4.189 | 25.1 | 56 | | | | | | |
| 884102 | 97 | 4.205 | 4.184 | 23.1 | 60 | | | | | | |
| 884103 | 207 | 4.212 | 4.185 | 24.1 | 48 | | | | | | |
| 884104 | 144 | 4.197 | 4.204 | 22.3 | 59 | | | | | | |
| 884105 | 116 | 4.195 | 4.203 | 23.1 | 48 | | | | | | |
| 884106 | 78 | 4.203 | 4.194 | 25.1 | 55 | | | | | | |
| 884201 | 134 | 4.186 | 4.172 | 23.1 | 56 | | | | | | |
| 884202 | 98 | 4.193 | 4.186 | 24.1 | 60 | | | | | | |
| 884203 | 217 | 4.197 | 4.228 | 22.0 | 52 | | | | | | |
| 884204 | 145 | 4.243 | 4.198 | 22.7 | 60 | | | | | | |
| 884205 | 165 | 4.217 | 4.180 | 24.4 | 52 | | | | | | |
| 884206 | 44 | 4.235 | 4.171 | 23.1 | 52 | | | | | | |
| 884301 | 154 | 4.205 | 4.179 | 25.1 | 60 | | | | | | |
| 884302 | 142 | 4.186 | 4.196 | 21.3 | 54 | | | | | | |
| 884303 | 143 | 4.191 | 4.199 | 22.0 | 54 | | | | | | |
| 884304 | 48 | 4.238 | 4.176 | 23.1 | 58 | | | | | | |
| 884305 | 81 | 15.397 | 23.622 | 20.0 | 46 | 24.998 | 51.998 | .5 | 3 | .5 | 0 |
| 884306 | 89 | 15.408 | 23.634 | 21.2 | 46 | 24.999 | 51.996 | 1.5 | 3 | .5 | 0 |
| 884401 | 9 | 15.403 | 23.627 | 19.2 | 43 | 25.000 | 51.999 | 1 | 2 | 1.5 | 0 |
| 884402 | 22 | 15.398 | 23.621 | 19.6 | 42 | 24.999 | 51.997 | 3 | 2 | 0 | 0 |
| 884403 | 232 | 15.398 | 23.626 | 21.6 | 47 | 24.999 | 51.998 | 1 | 2 | 0 | 0 |
| 884404 | 190 | 15.402 | 23.629 | 21.6 | 50 | 24.998 | 51.997 | 1 | 2 | .5 | 1 |
| 884405 | 172 | 15.405 | 23.628 | 19.2 | 42 | 24.998 | 51.999 | 1 | 3 | .5 | 0 |
| 884406 | 187 | 15.399 | 23.626 | 19.4 | 45 | 24.998 | 51.998 | 1 | 3 | .25 | .5 |
| 884501 | 28 | 15.403 | 23.627 | 19.2 | 44 | 24.997 | 51.991 | 2 | 3 | 0 | 0 |
| 884502 | 32 | 15.407 | 23.634 | 19.4 | 45 | 24.996 | 51.998 | 1 | 3 | .5 | .5 |
| 884503 | 155 | 15.401 | 23.625 | 20.0 | 42 | 24.998 | 51.996 | 2 | 3 | .5 | .5 |
| 884504 | 148 | 15.402 | 23.627 | 19.6 | 42 | 25.000 | 51.998 | .5 | 3 | .5 | 0 |
| 884505 | 100 | 15.407 | 23.631 | 19.2 | 40 | 24.997 | 51.997 | 3 | 2 | .5 | 0 |
| 884506 | 106 | 15.404 | 23.629 | 19.6 | 40 | 24.999 | 51.997 | 2 | 3 | 1 | .5 |
| 884601 | 94 | 15.397 | 23.627 | 23.7 | 55 | 24.998 | 51.998 | 1 | 3 | 0 | .5 |
| 884602 | 23 | 15.406 | 23.631 | 20.0 | 43 | 24.997 | 51.996 | 2 | 3 | .5 | .5 |
| 884603 | 159 | 15.403 | 23.629 | 20.8 | 45 | 24.999 | 51.997 | 1 | 2 | 0 | .5 |
| 884604 | 169 | 15.406 | 23.630 | 19.6 | 40 | 24.997 | 51.999 | 1 | 4 | .5 | 0 |
| 884605 | 248 | 15.406 | 23.624 | 17.9 | 36 | 24.998 | 51.996 | 3 | 2 | .5 | 0 |
| 884606 | 249 | 15.401 | 23.621 | 19.2 | 38 | 24.998 | 51.999 | 1 | 3 | .5 | 0 |
| 884701 | 231 | 15.406 | 23.631 | 21.2 | 47 | 24.998 | 51.996 | 2 | 3 | 0 | 0 |
| 884702 | 110 | 15.401 | 23.624 | 18.8 | 39 | 24.998 | 51.997 | 1 | 3 | 0 | .5 |
| 884703 | 124 | 15.401 | 23.624 | 18.5 | 37 | 24.998 | 51.997 | 1 | 3 | 0 | .5 |
| 884704 | 247 | 15.393 | 23.622 | 24.4 | 60 | 24.998 | 51.998 | 2 | 2 | 1 | 1 |
| 884705 | 15 | 15.402 | 23.627 | 22.1 | 40 | 24.998 | 51.997 | 1 | 2 | 0 | 0 |
| 884706 | 5 | 15.406 | 23.628 | 21.3 | 43 | 24.998 | 51.998 | 1 | 2 | 1 | 1 |
| 884805 | 161 | 15.410 | 23.634 | 22.4 | 46 | 24.998 | 51.996 | 2 | 2 | .5 | 1 |
| 884806 | 12 | 15.404 | 23.627 | 17.7 | 43 | 24.998 | 51.999 | 1 | 2 | 0 | 1 |

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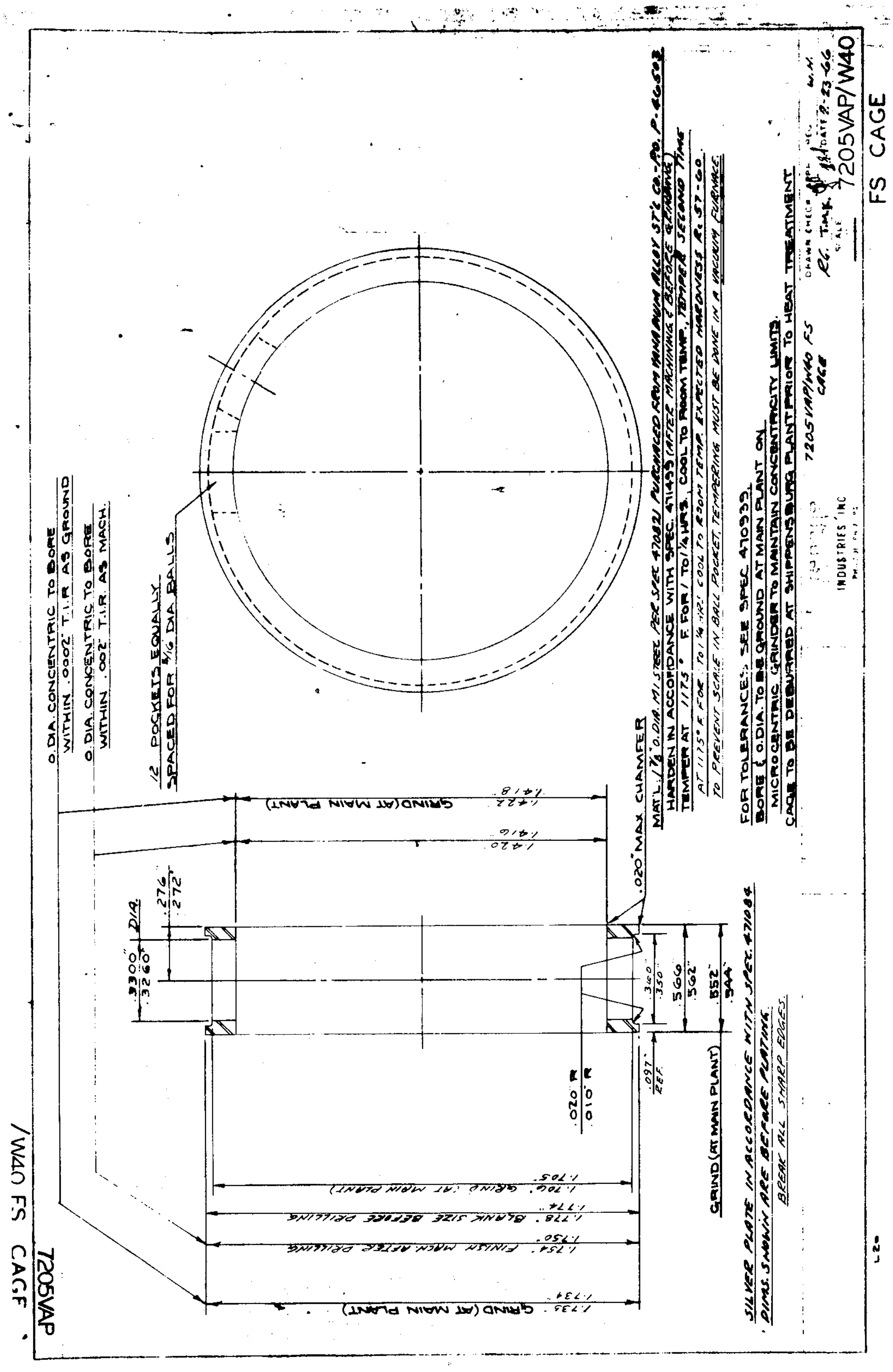
# ENCLOSURE 10

7205 VAP TEST BEARING CAGE (OUTER RING GUIDED)



# ENCLOSURE 11

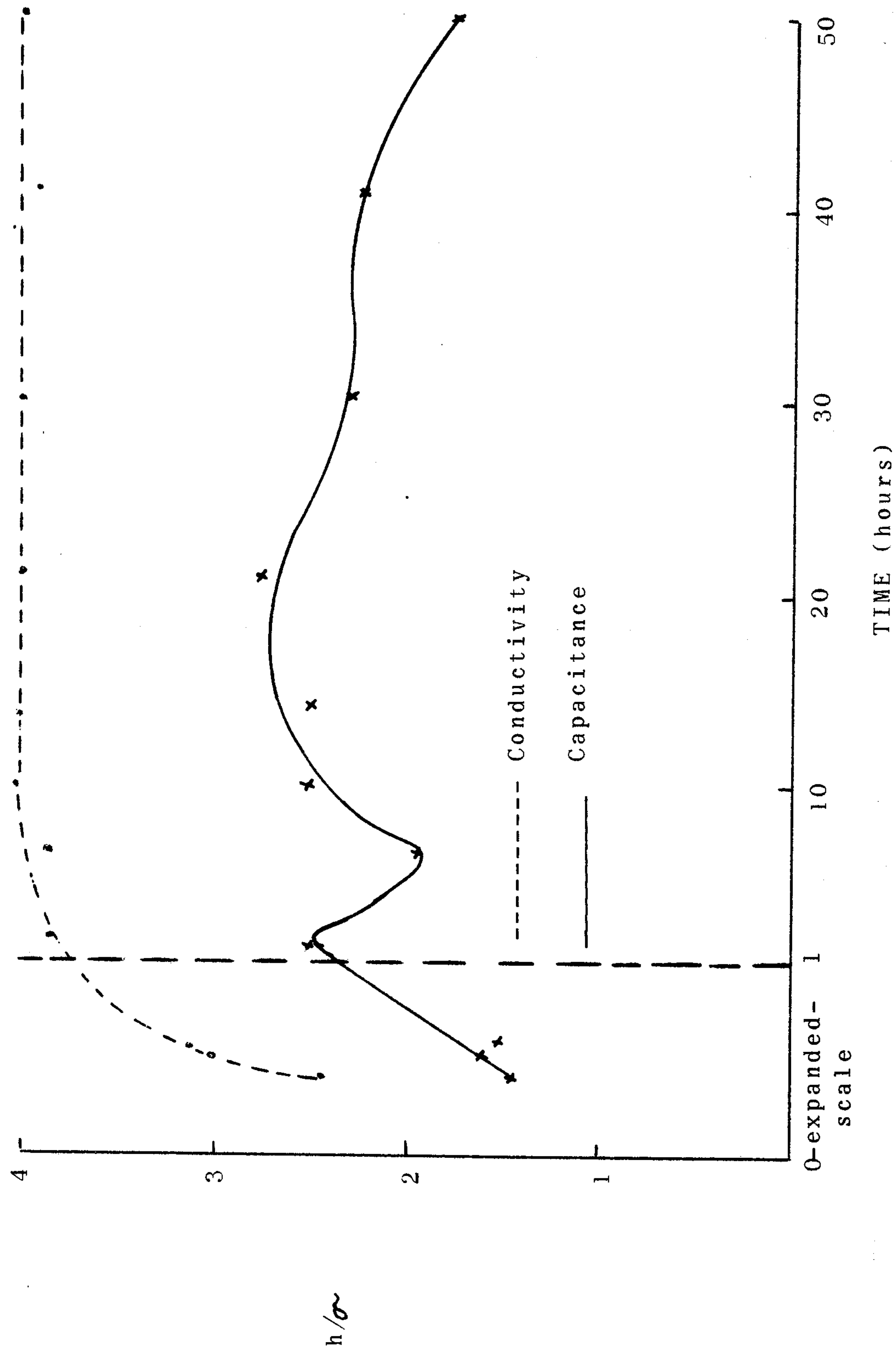
SUMMARY OF TEST RESULTS

| Test No. | Lubricant | Bearings | Life Hrs. | Life Mill.revs. | Results | h/σ |
|---|---|---|---|---|---|---|
| 1A | Mobil XRM-109F | 7205 VAP | 14.3 | 36.9 | (l)* IR and OR glazed and pitted.<br>(d) Spalled ball, IR and OR glazed. | |
| 1B | Mobil XRM-109F | 7205 VAP | 0.3 | 0.8 | (l) IR and OR highly glazed and lightly micropitted.<br>(d) IR and OR highly glazed and lightly micropitted. | |
| 1C | Mobil XRM-109F | 7205 VAP | 50 | 129 | (l) IR lightly pitted, OR good condition.<br>(d)**IR and OR lightly pitted. | 3.5-4.0 |
| 1C (Aborted)*** | Mobil XRM-109F | 7205 VAP | 20.4 | 52.6 | (l) IR and OR highly glazed and pitted.<br>(d) IR and OR highly glazed and pitted. | |
| 2A | Monsanto MCS-2931 | 7205 VAP | 46.9 | 121 | (l) Good condition.<br>(d) IR spalled. | |
| 2B | Monsanto MCS-2931 | 7205 VAP | 100 | 258 | (l) IR good, OR pitted.<br>(d) IR good, OR pitted. | |
| 2C | Monsanto MCS-2931 | 7205 VAP | 42.8 | 111 | (l) IR and OR pitted.<br>(d)**IR spalled. | <1.8 |
| 2C (Aborted)*** | Monsanto MCS-2931 | 7205 VAP | 3.5 | 9.0 | (l) Good condition.<br>(d) Good condition. | |
| 3A | Humble FN-3158 | 7205 VAP | 71.1 | 183 | (l) IR, OR and balls smeared.<br>(d) IR and OR heavily pitted. | |
| 3B | Humble FN-3158 | 7205 VAP | 40.3 | 104 | (l) IR pitted, OR glazed.<br>(d) IR spalled, OR spalled. | |
| 3C | Humble FN-3158 | 7205 VAP-3 | 50 | 129 | (l) IR spalled, OR micropitted.<br>(d) IR good condition, OR debris denting. | 2.6-3.6(11.1 hrs)<br><1.8 (38.9 hrs) |
| 4A | Humble FN-3158 plus 10% Kendall Resin | 7205 VAP-3 | 100 | 258 | (l) IR and OR lightly pitted.<br>(d) Good condition. | |
| 4B | Humble FN-3158 plus 10% Kendall Resin | 7205 VAP-3 | 100 | 258 | (l) Good condition.<br>(d) Good condition. | |
| 4C | Humble FN-3158 plus 10% Kendall Resin | 7205 VAP-3 | 50 | 129 | (l) Good condition.<br>(d) Good condition. | 3.6 - 4.0 |
| 5A | Dow Corning XF-1-0301 | 7205 VAP-3 | 100 | 258 | (l) IR and OR lightly pitted.<br>(d) Good condition but IR has uneven wear track. | |
| 5B | Dow Corning XF-1-0301 | 7205 VAP-3 | 100 | 258 | (l) IR, OR, and ball micropitted.<br>(d) IR and OR lightly pitted. | |
| 5C | Dow Corning XF-1-0301 | 7205 VAP-3 | 50 | 129 | (l) IR and OR lightly pitted.<br>(d) IR and OR lightly pitted. | <1.8 |
| 6A | Mobil XRM-109F plus 10% Kendall Resin | 7205 VAP-3 | 100 | 258 | (l) IR and OR micropitted.<br>(d) IR and OR lightly glazed and pitted. | |
| 6B | Mobil XRM-109F plus 10% Kendall Resin | 7205 VAP-3 | 100 | 258 | (l) IR and OR glazed and micropitted.<br>(d) IR and OR glazed and micropitted. | |
| 6C | Mobil XRM-109F plus 10% Kendall Resin | 7205 VAP-3 | 50 | 129 | (l) IR and OR lightly glazed and micropitted.<br>(d) IR good condition, OR micropitted. | <1.8 |
| 7A | Esso AL07873 | 7205 VAP-3 | 100 | 258 | (l) IR and OR glazed and pitted, one spalled ball.<br>(d) IR and OR glazed and pitted, one spalled ball. | |
| 7B | Esso AL07873 | 7205 VAP-3 | 100 | 258 | (l) All balls spalled, IR and OR moderately glazed, pitted, & dented.<br>(d) Two balls spalled, IR and OR highly glazed. | |
| 7C | Esso AL07873 | 7205 VAP-3 | 50 | 129 | (l) IR and OR glazed and micropitted, spalled balls.<br>(d) IR and OR glazed and micropitted, spalled balls. | <1.8 |
| 8C | DuPont Krytox 143AB (with additive) | 7205 VAP-3 | 50 | 129 | (l) IR good, OR lightly micropitted.<br>(d) IR good, OR lightly micropitted and slightly uneven wear track. | 3.0-4.0(7.6 hrs)<br><1.8 (42.4 hrs) |

* (l) and (d) denote "load-end" and "drive-end" bearings respectively.
** Bearing Black-oxide coated.
*** Film measurements (h/σ) unavailable for aborted tests.

ENCLOSURE 12

PLOT OF h/σ VS. TIME FOR TEST #1C USING MOBIL XRM-109F



F-4186 A R 100

BIND

ENCLOSURE 13

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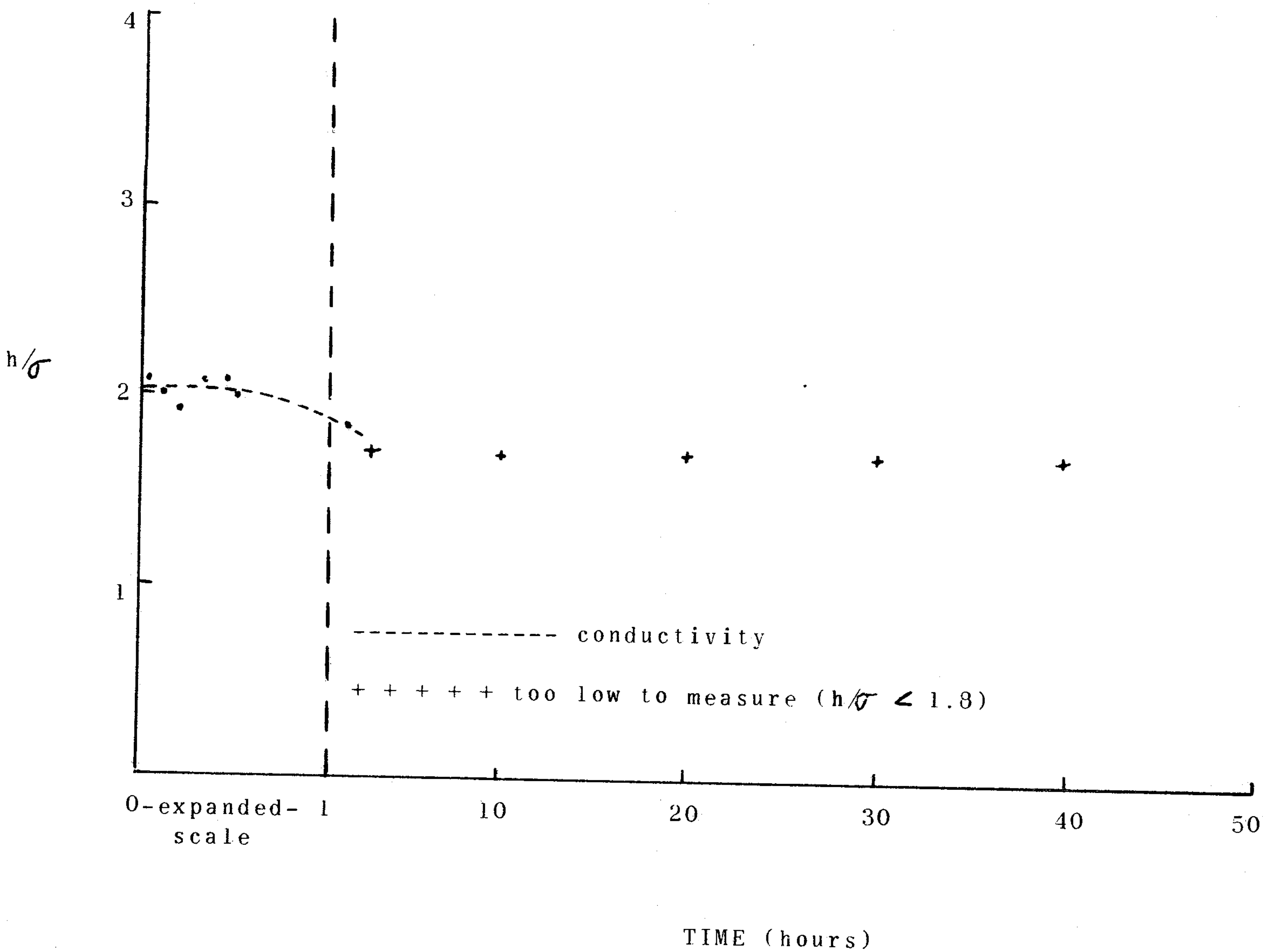
PLOT OF h/σ VS. TIME FOR TEST #2C USING MONSANTO MCS 2931

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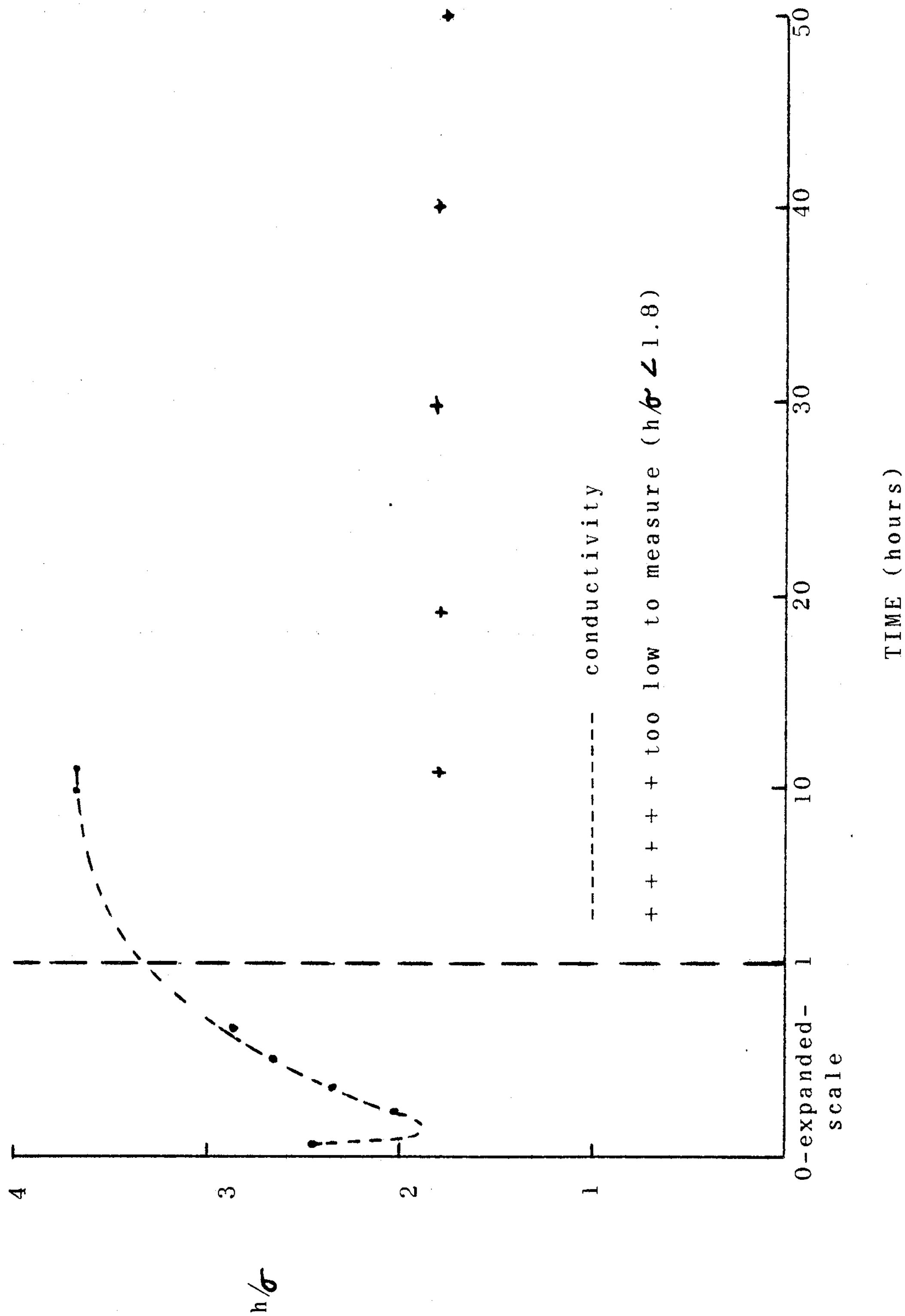
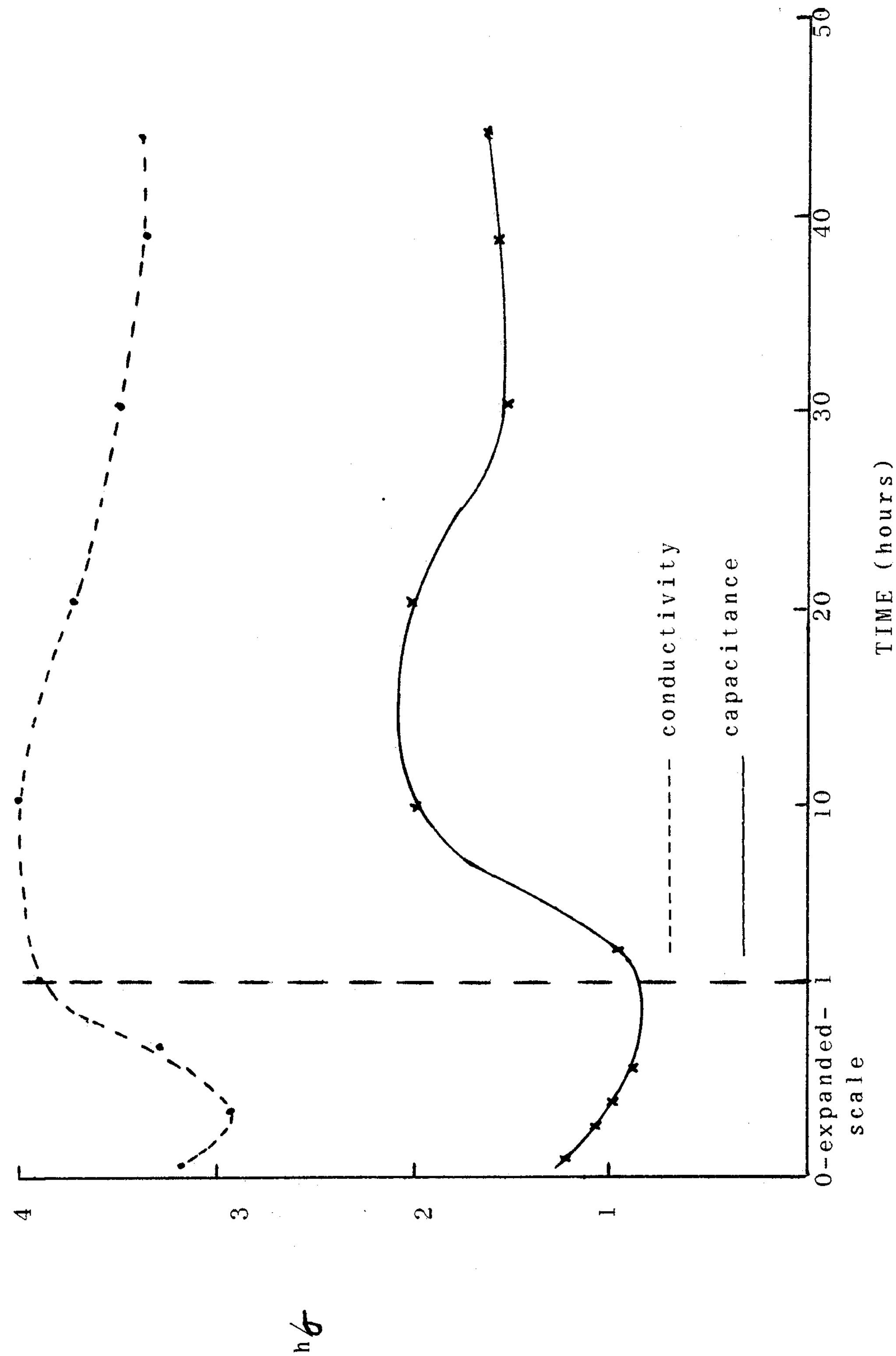
ENCLOSURE 14

PLOT OF h/σ VS. TIME FOR TEST #3C USING HUMBLE FN-3158 LUBRICANT



ENCLOSURE 15

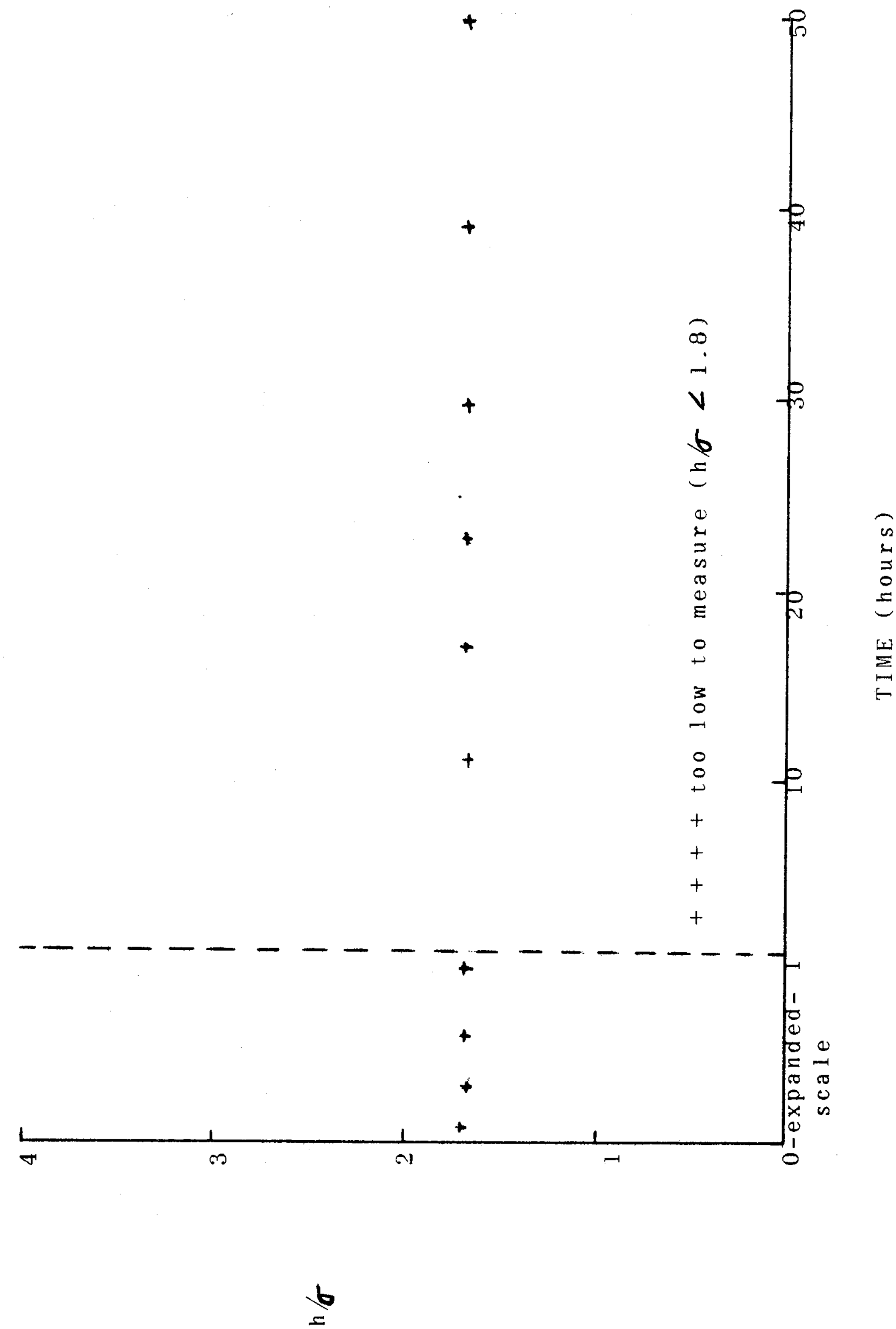
PLOT OF h/σ VS. TIME FOR TEST #4C USING HUMBLE FN-3158 PLUS 10% KENDALL RESIN




F-4186 A R 100

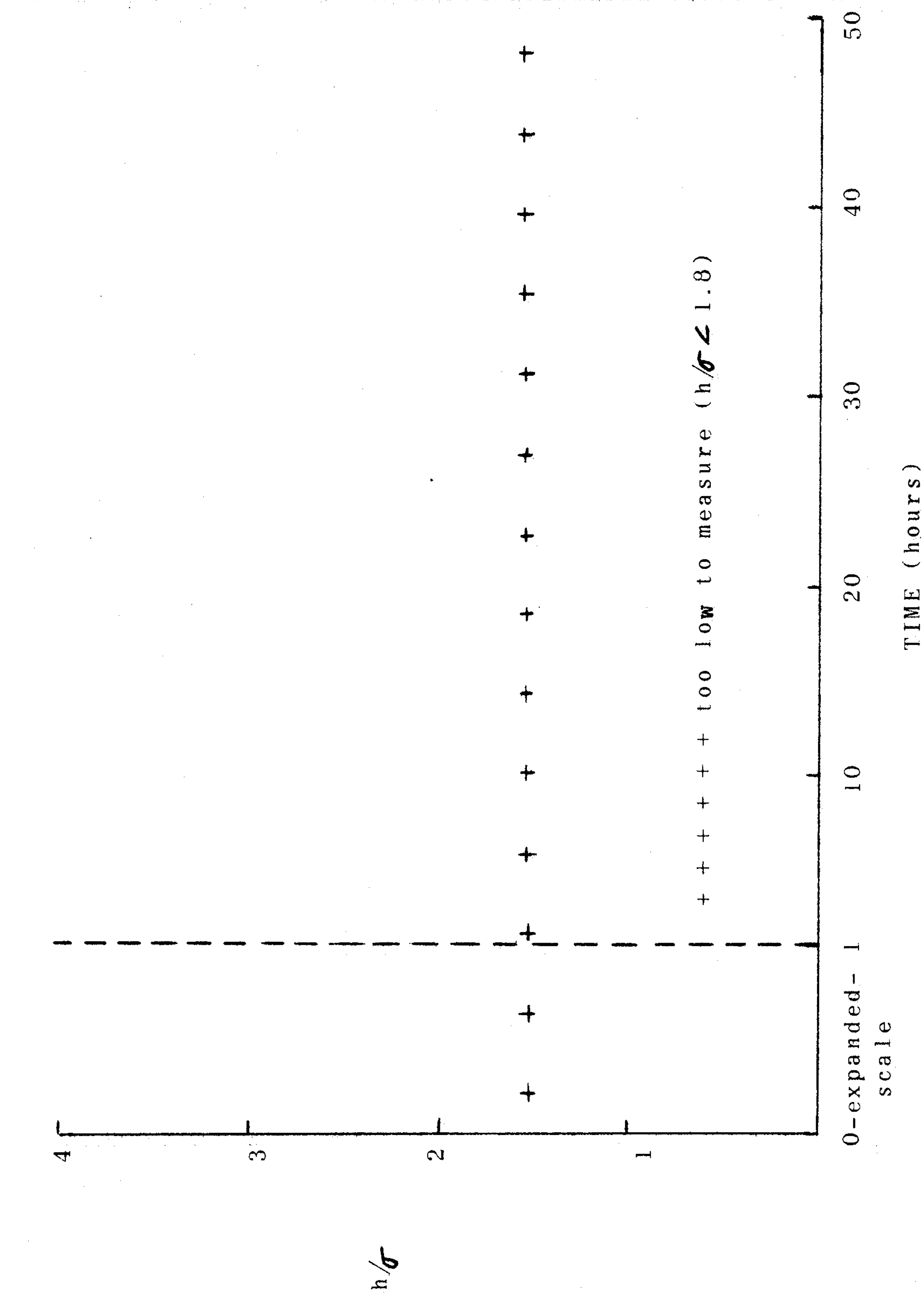
ENCLOSURE 16

PLOT OF $h/\sigma$ VS. TIME FOR TEST #5C USING DOW CORNING XF-1-0301



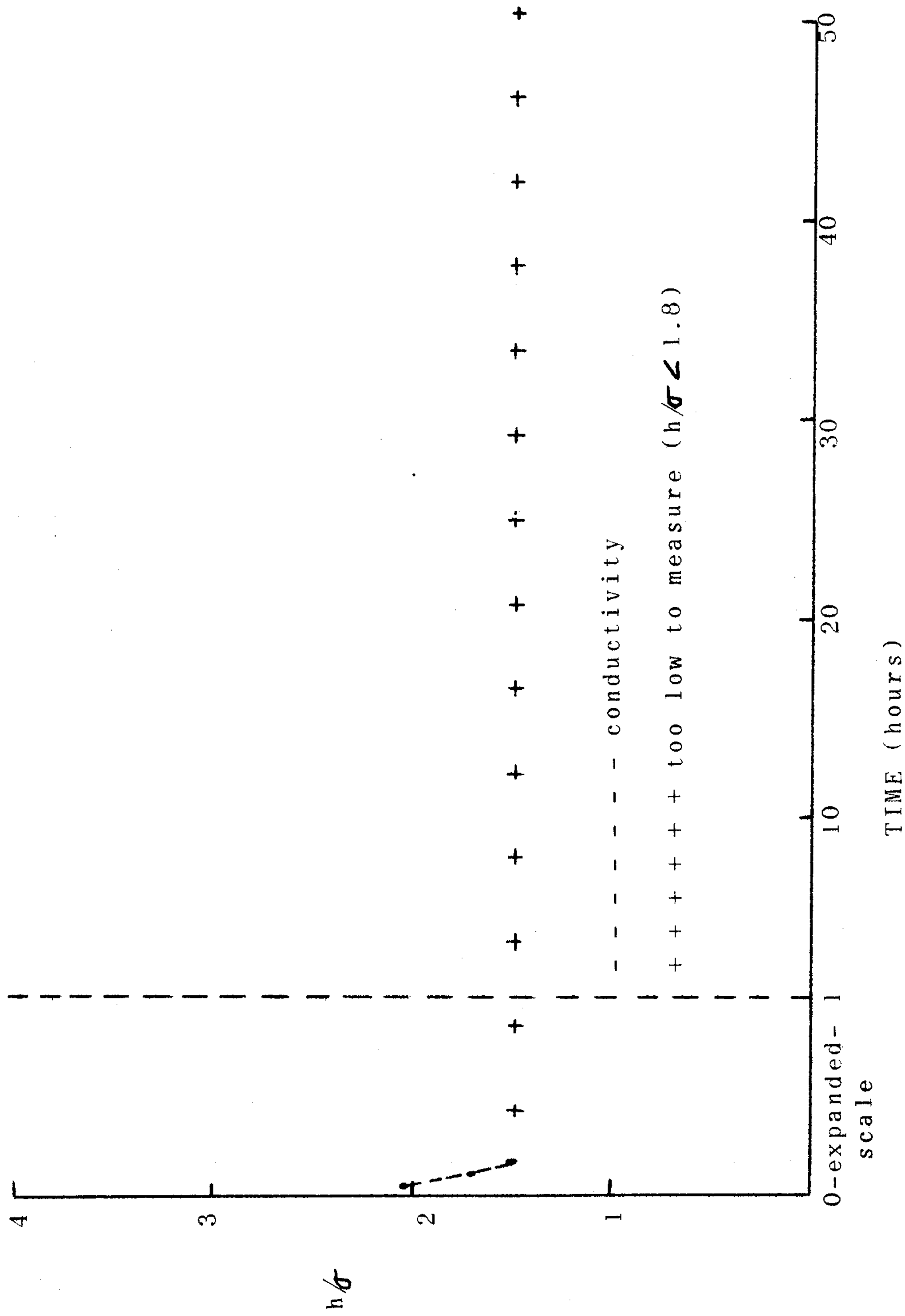
ENCLOSURE 17

PLOT OF h/σ VS. TIME FOR TEST #6C USING MOBIL XRM-109F PLUS 10% KENDALL RESIN



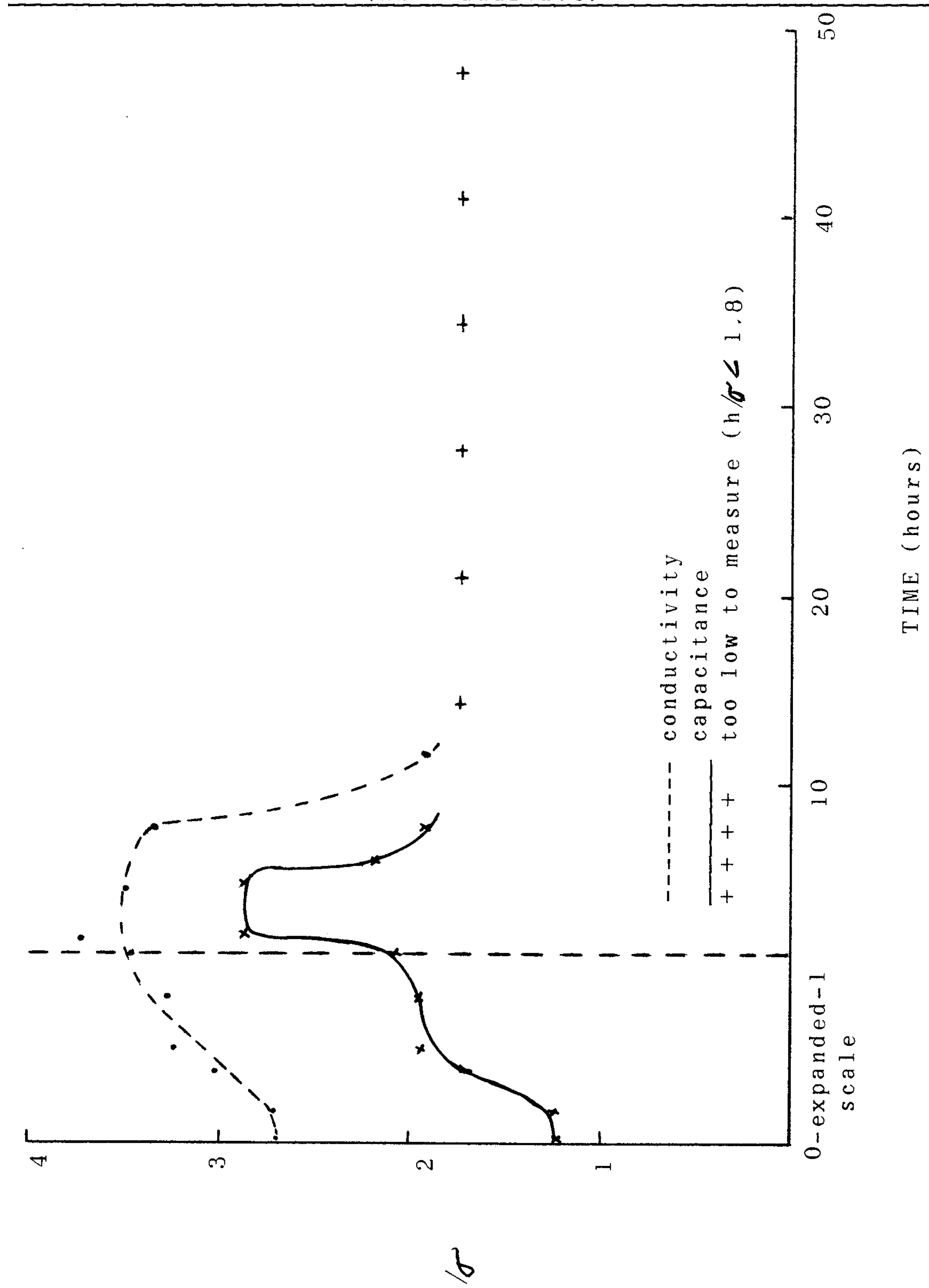
ENCLOSURE 18

PLOT OF h/σ VS. TIME FOR TEST #7C USING ESSO AL07873



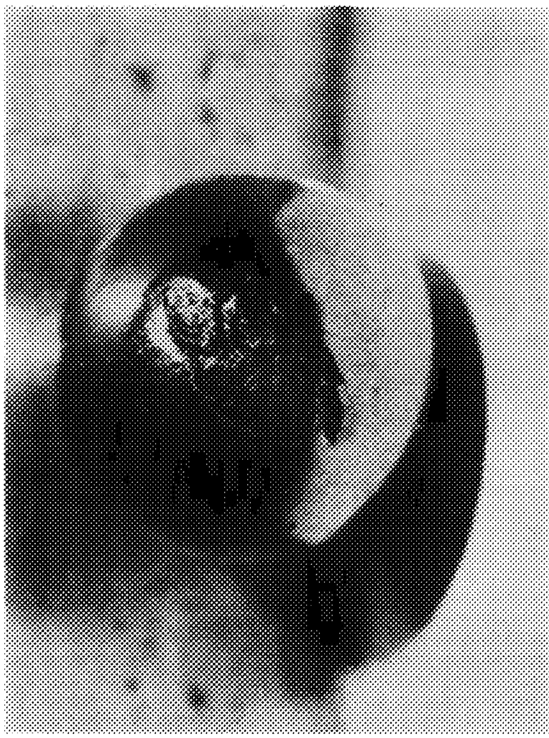
ENCLOSURE 19

PLOT OF h/σ VS. TIME FOR TEST #8C USING DU PONT KRYTOX 143AB
(with additive)

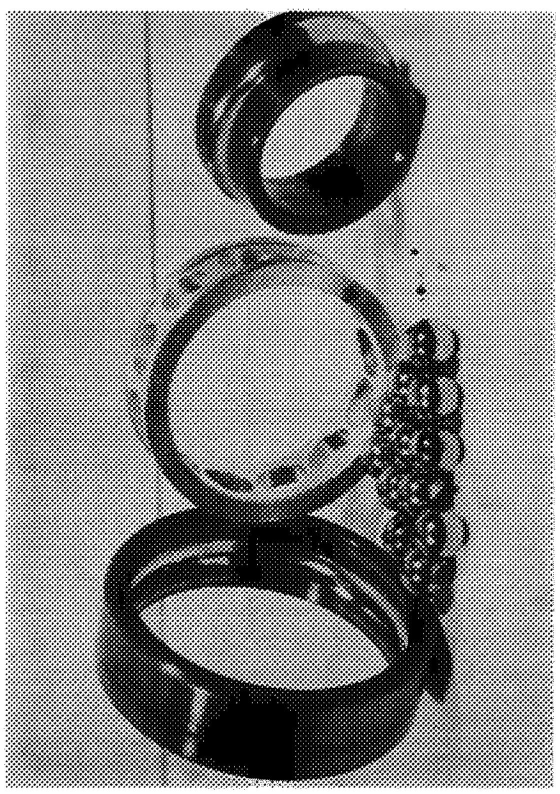


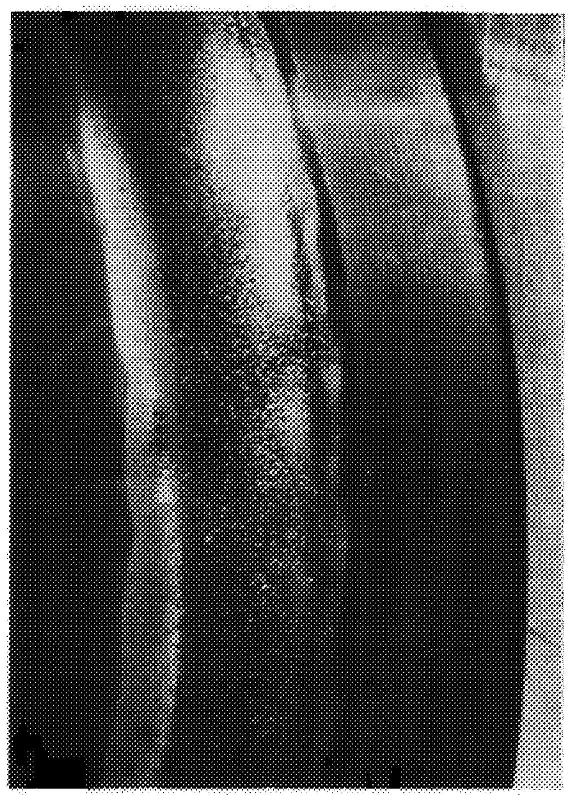
ENCLOSURE 20

TEST BEARING #102 FROM TEST #IA USING MOBIL XRM-109F
AFTER 14.3 HOURS AT 600°F



OUTER RACE

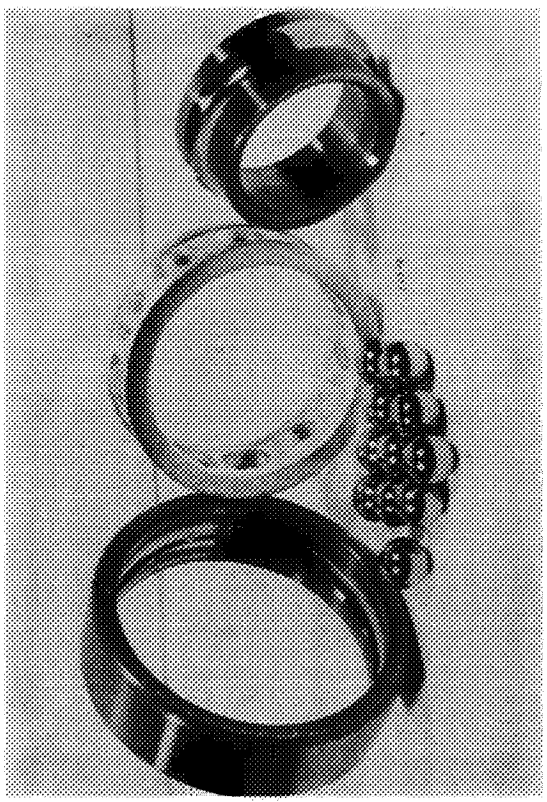


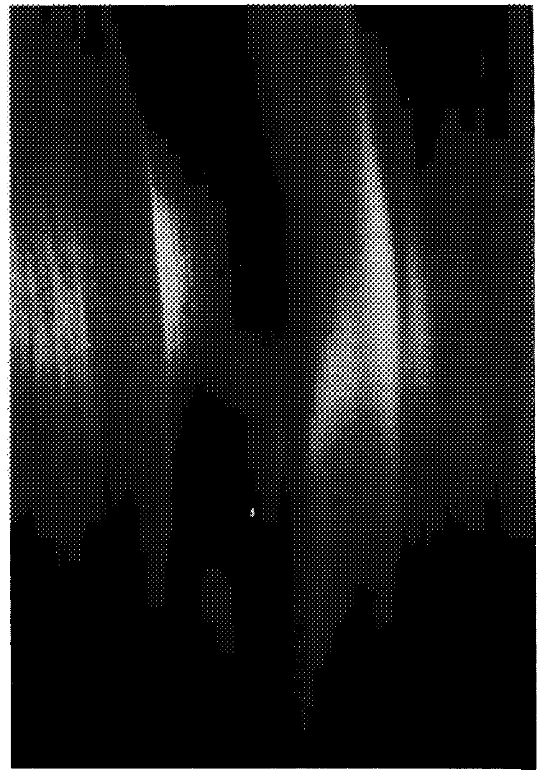


INNER RACE

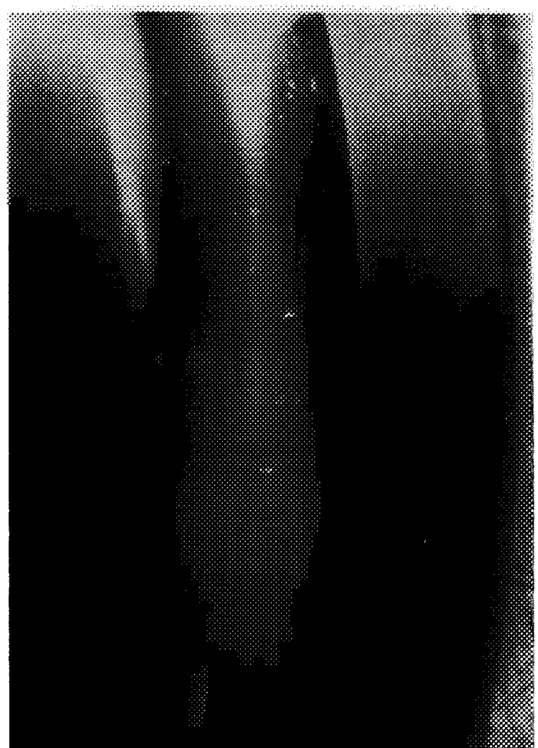
ENCLOSURE 21

TEST BEARING #104 FROM TEST #IB USING MOBIL XRM-109F
AFTER 0.3 HOURS AT 600°F





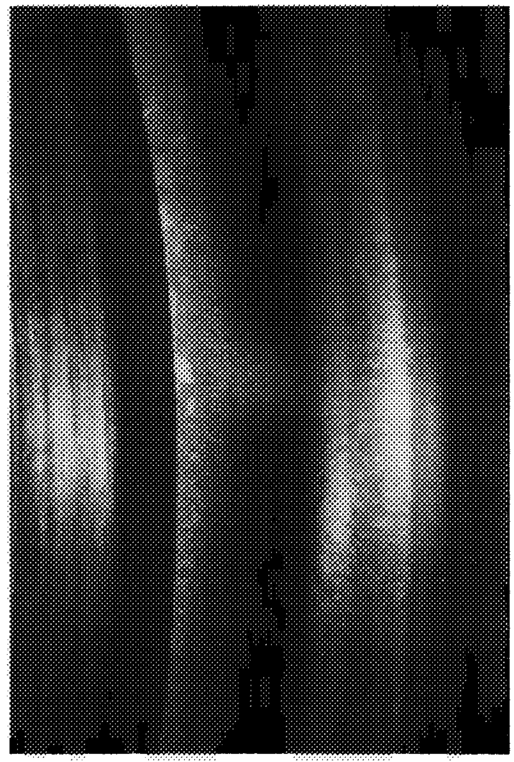
OUTER RACE



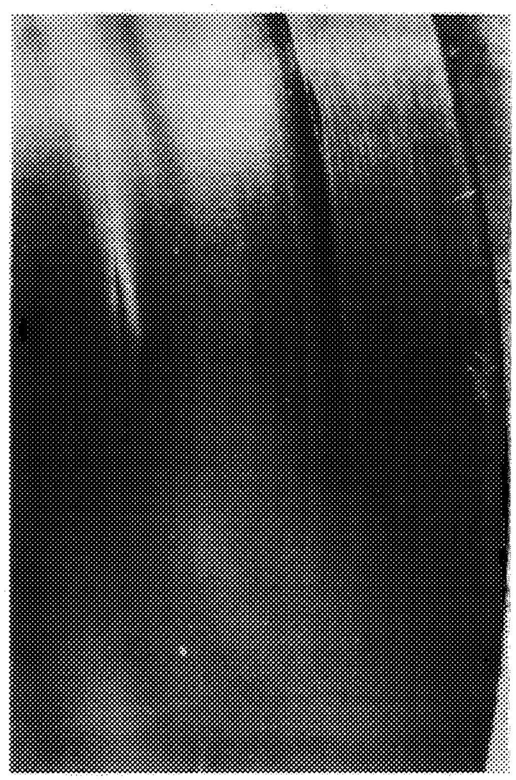
INNER RACE

ENCLOSURE 22

TEST BEARING #105 FROM TEST #IC USING MOBIL XRM-109F
AFTER 50 HOURS AT 600°F



OUTER RACE

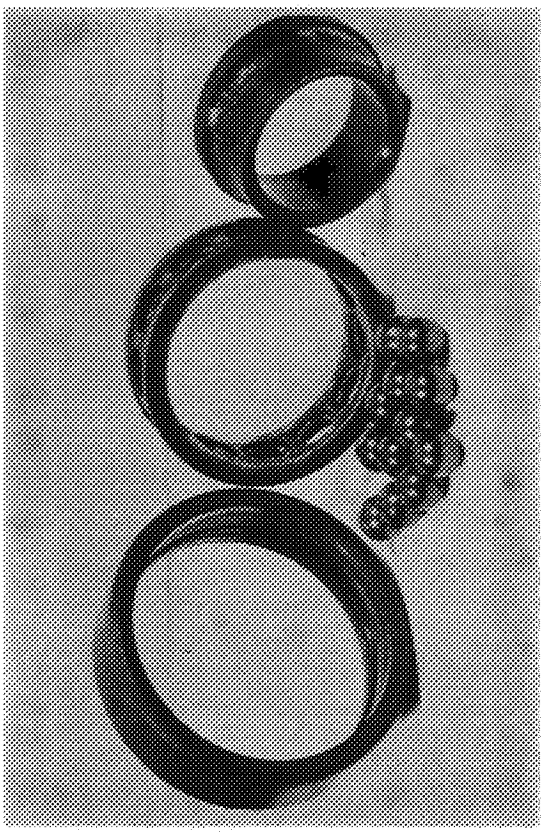


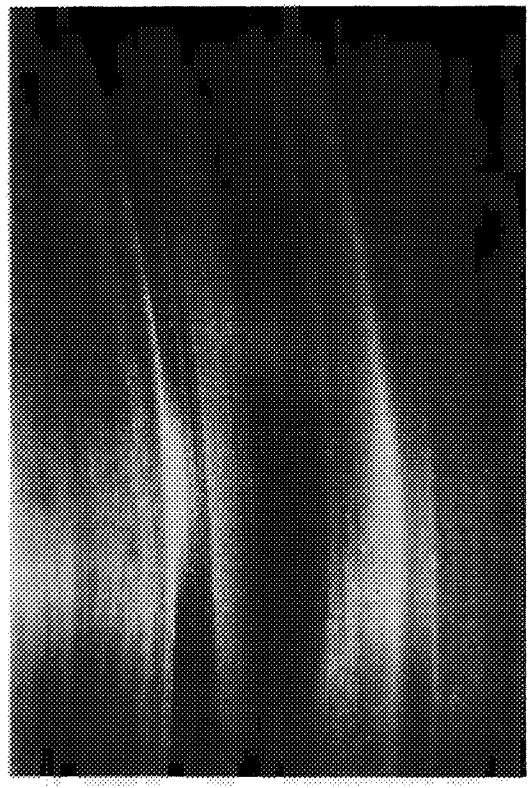
INNER RACE

ENCLOSURE 23

TEST BEARING #202 FROM TEST #2A USING MONSANTO MCS-2931

AFTER 46.9 HOURS AT 600°F



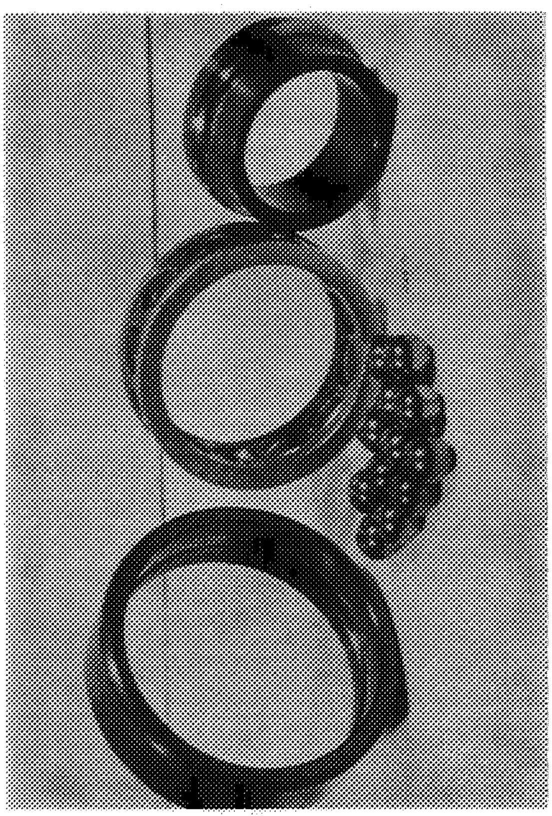


OUTER RACE

INNER RACE

ENCLOSURE 24

TEST BEARING #203 FROM TEST #2B USING MONSANTO MCS-2931
AFTER 100 HOURS AT 600°F



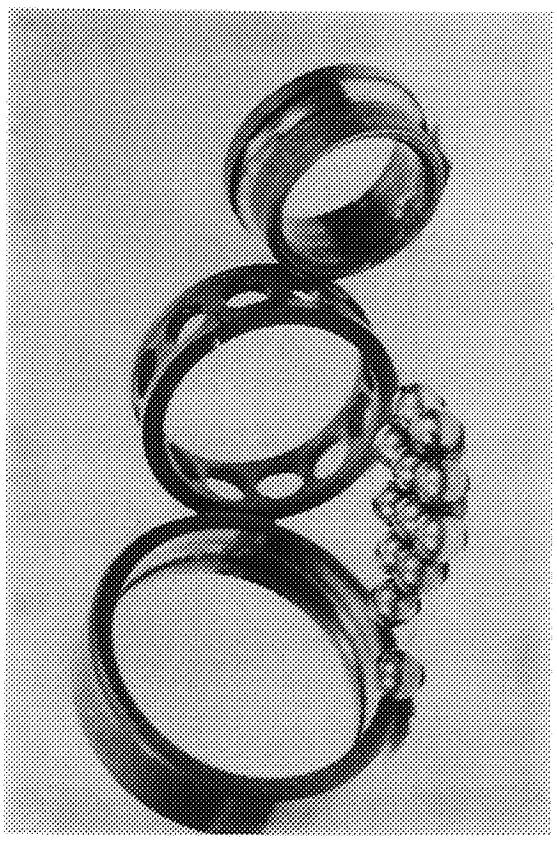
OUTER RACE

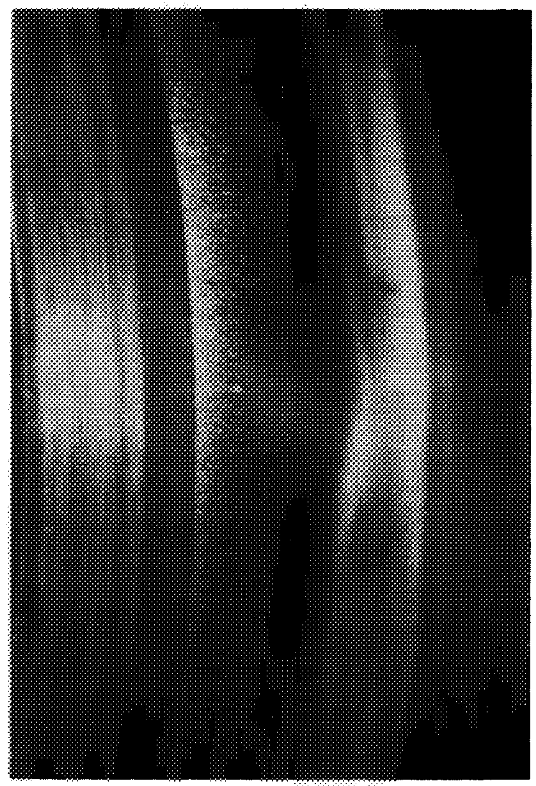
INNER RACE

ENCLOSURE 25

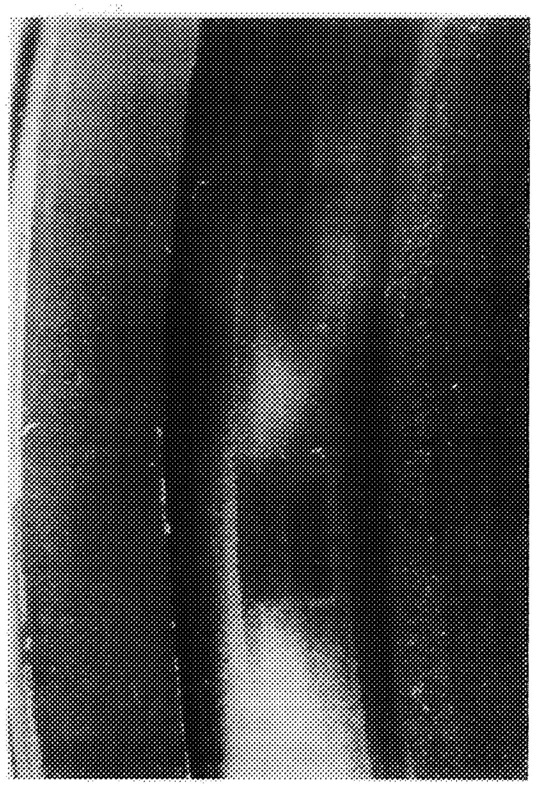
TEST BEARING #205 FROM TEST #2C USING MONSANTO MCS-2931

AFTER 42.3 HOURS AT 600°F





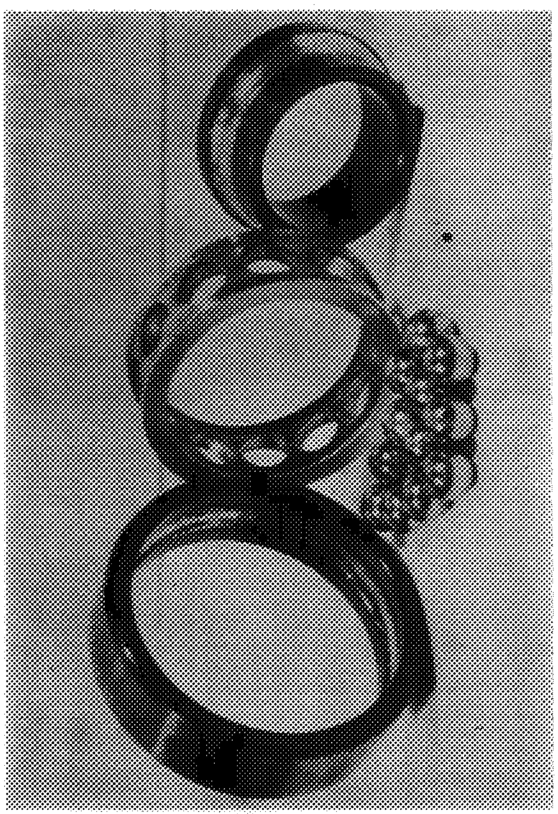
OUTER RACE



INNER RACE

ENCLOSURE 26

TEST BEARING #301 FROM TEST #3A USING HUMBLE FN-3158
AFTER 71.1 HOURS AT 600°F

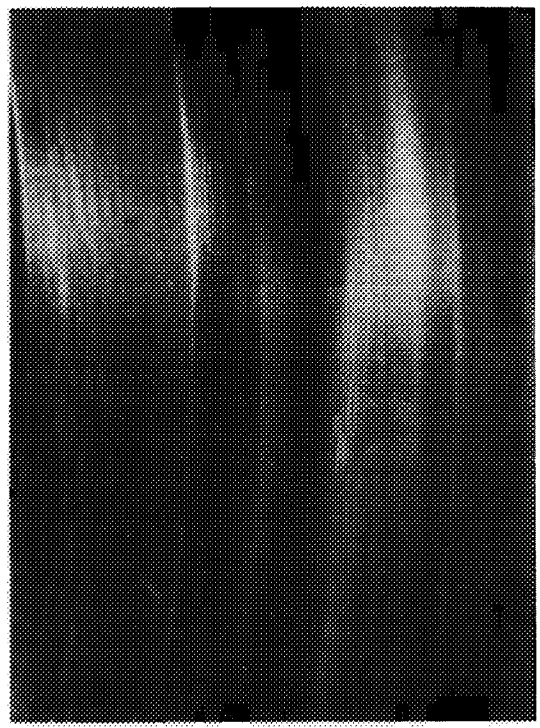


OUTER RACE

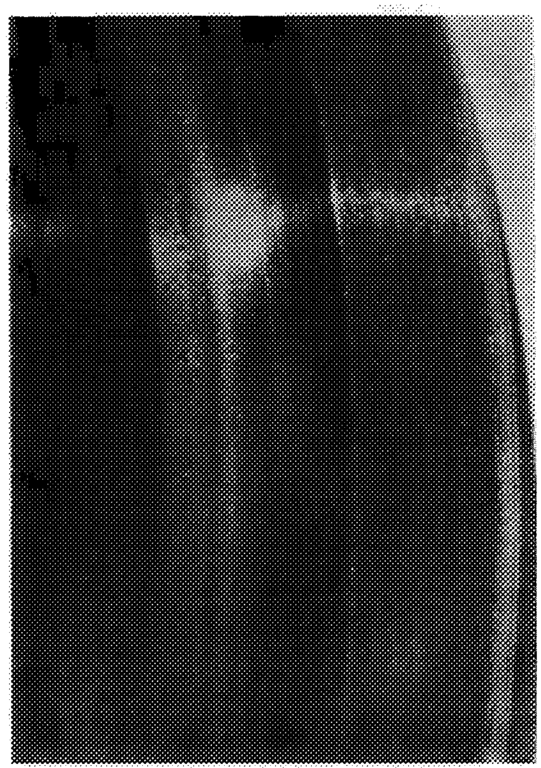
INNER RACE

ENCLOSURE 27

TEST BEARING #303 FROM TEST #3B USING HUMBLE FN-3158
AFTER 40.3 HOURS AT 600°F



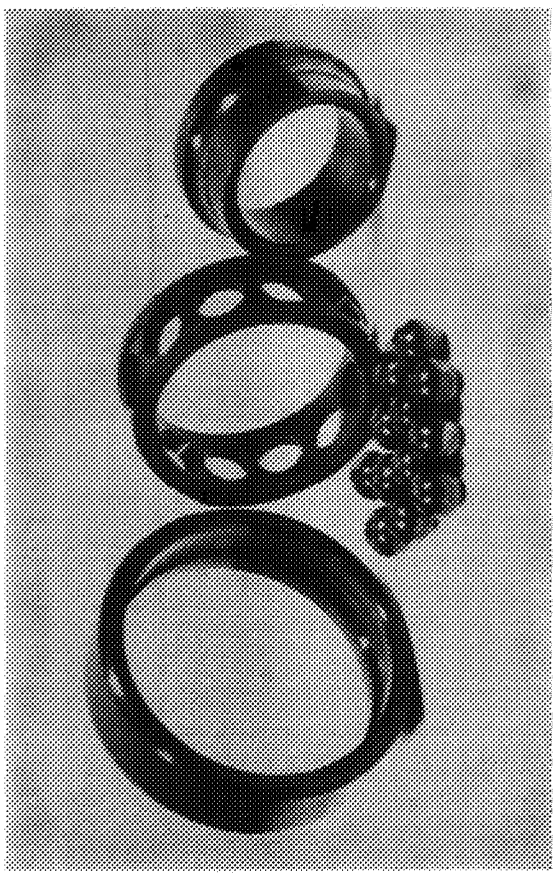
OUTER RACE



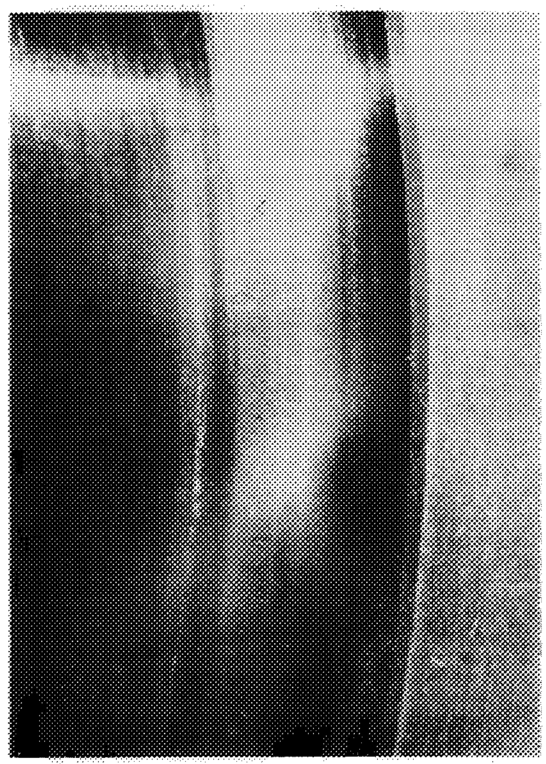
INNER RACE

ENCLOSURE 28

TEST BEARING #305 FROM TEST #3C USING HUMBLE FN-3158
AFTER 50 HOURS AT 600°F



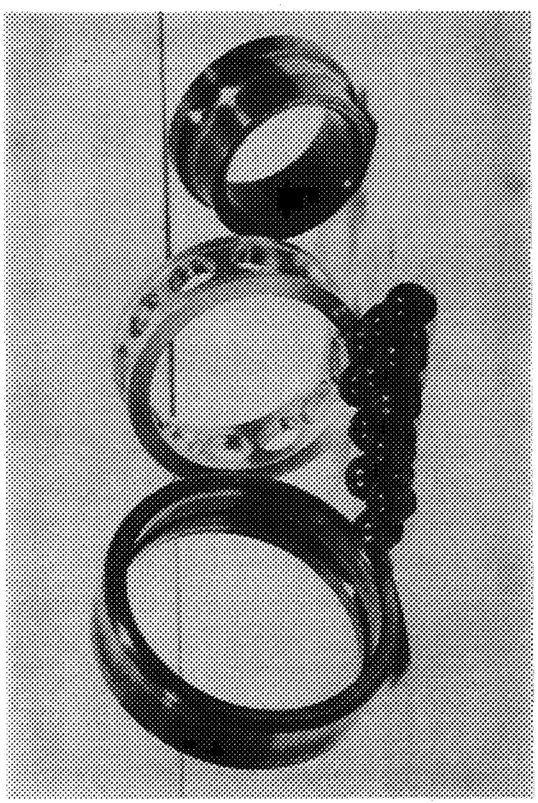
OUTER RACE

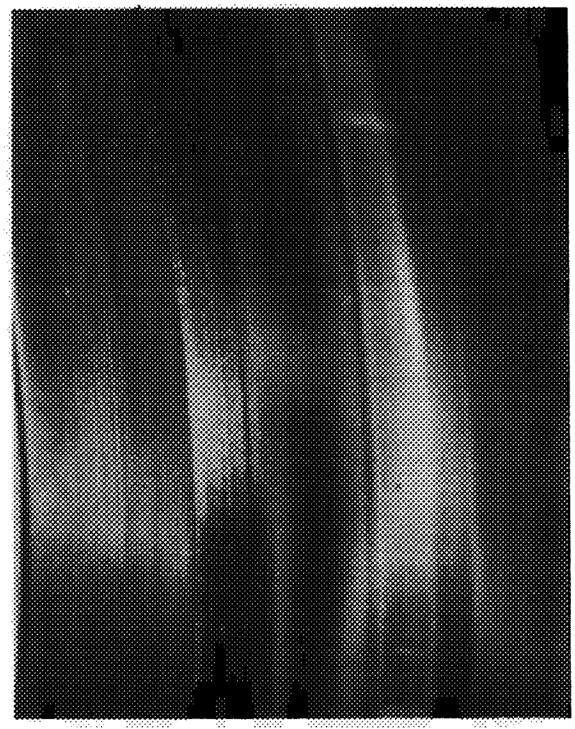


INNER RACE

ENCLOSURE 29

TEST BEARING #401 FROM TEST #4A USING HUMBLE FN-3158 PLUS 10%
KENDALL RESIN
AFTER 100 HOURS AT 600°F





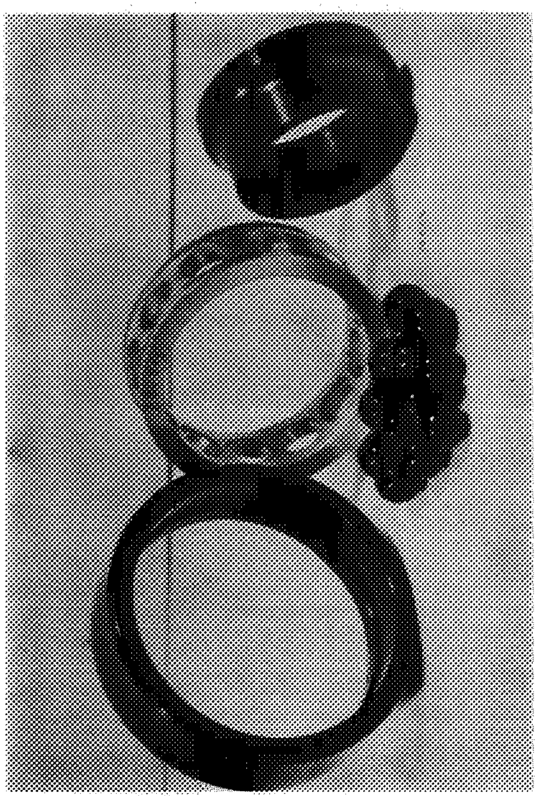
OUTER RACE

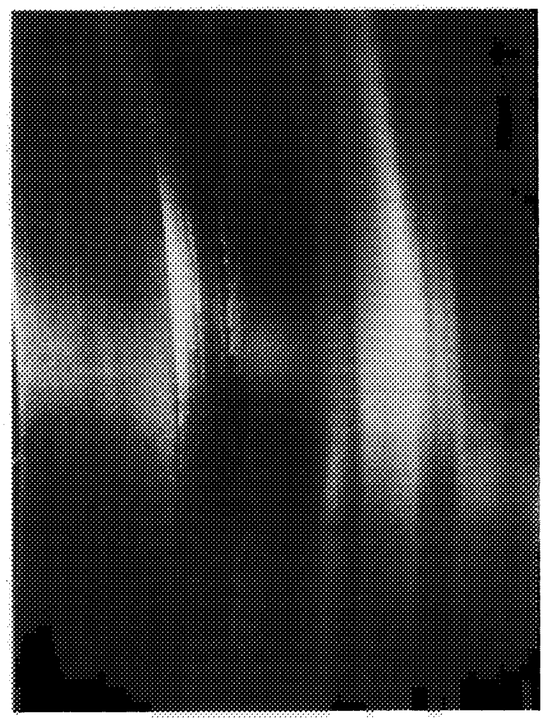
INNER RACE

ENCLOSURE 30

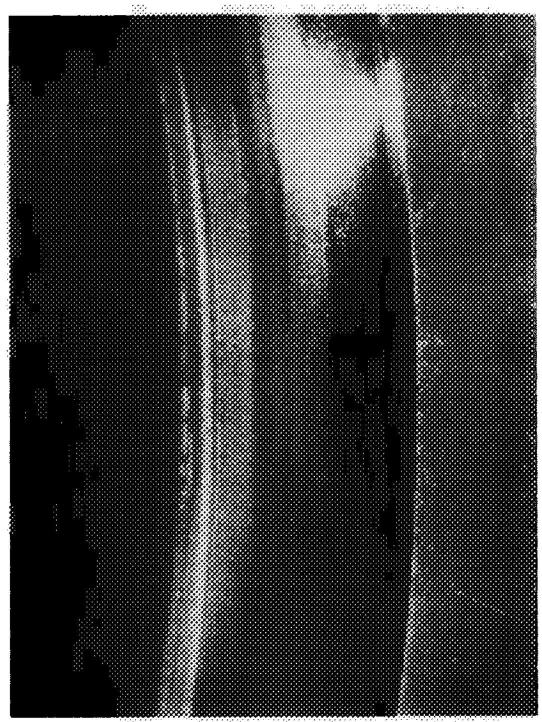
TEST BEARING #403 FROM TEST #4B USING HUMBLE FN-3158 PLUS 10% KENDALL RESIN

AFTER 100 HOURS AT 600°F





OUTER RACE

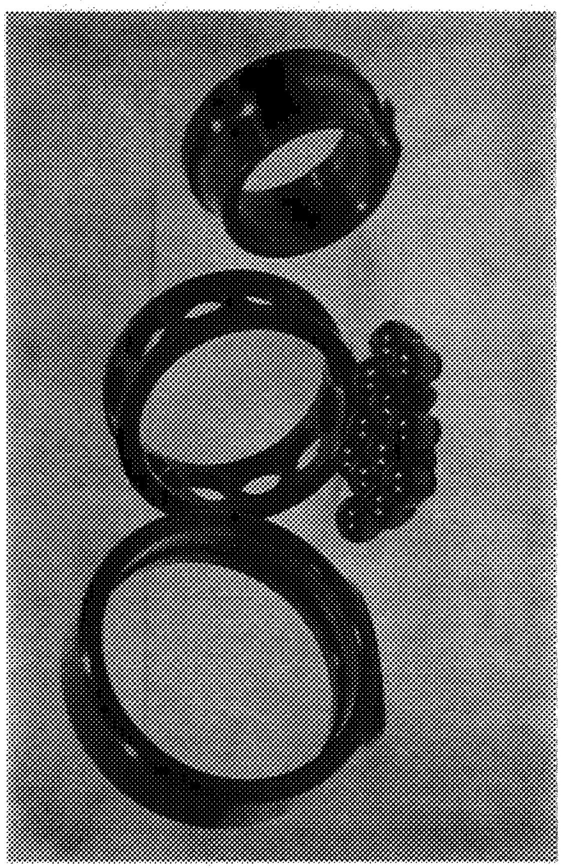


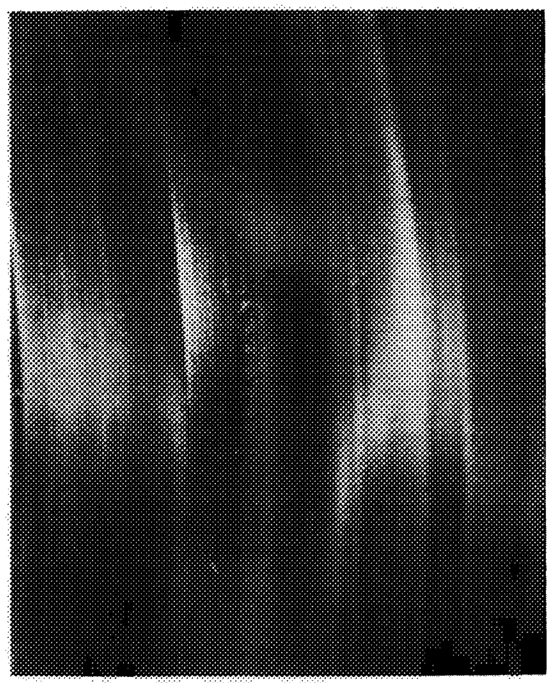
INNER RACE

ENCLOSURE 31

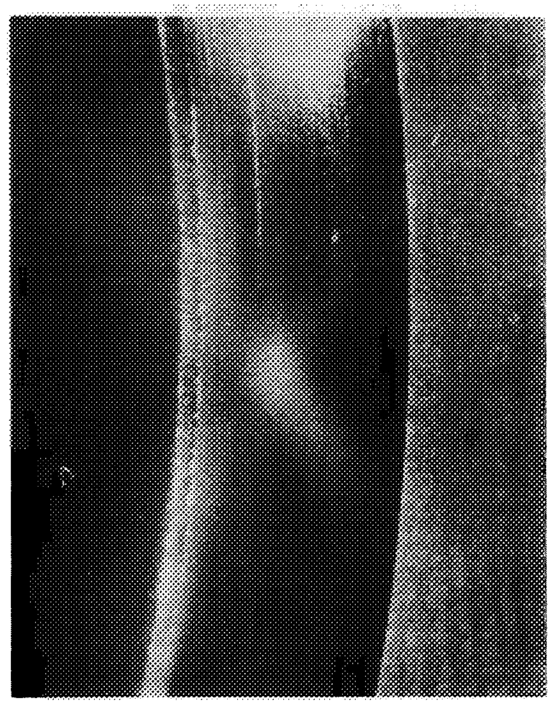
TEST BEARING #405 FROM TEST #4C USING HUMBLE FN-3158 PLUS 10%
KENDALL RESIN

AFTER 50 HOURS AT 600°F





OUTER RACE

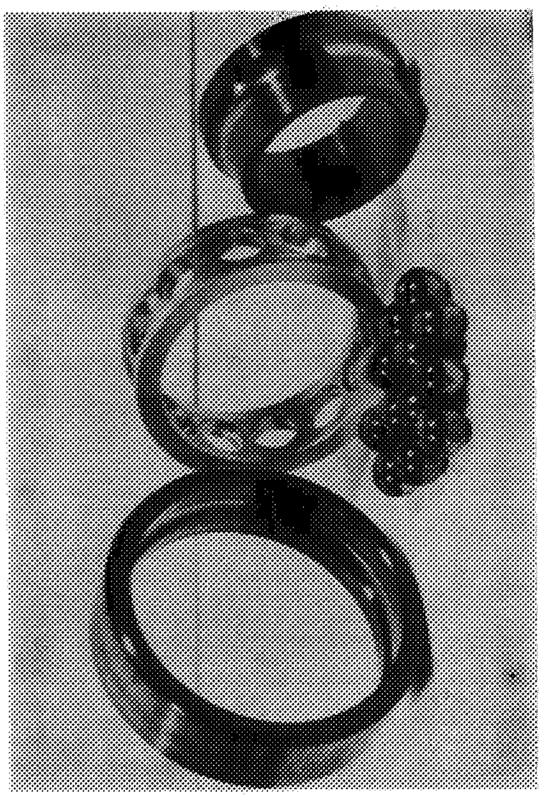


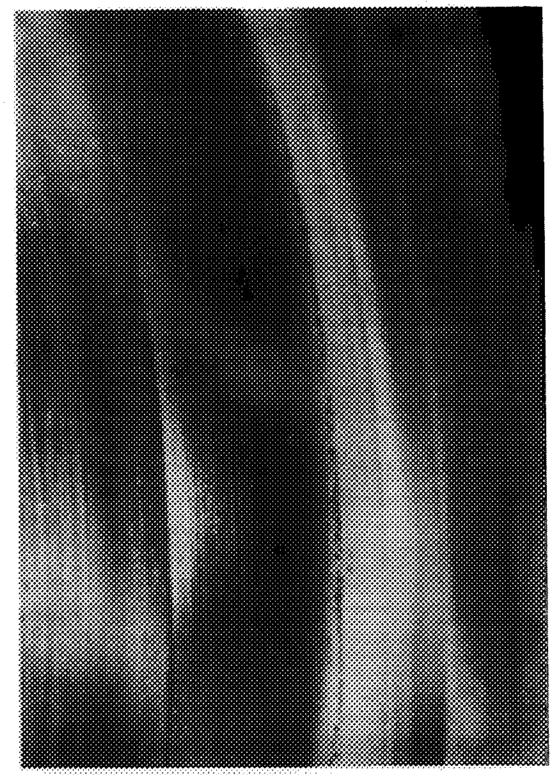
INNER RACE

ENCLOSURE 32

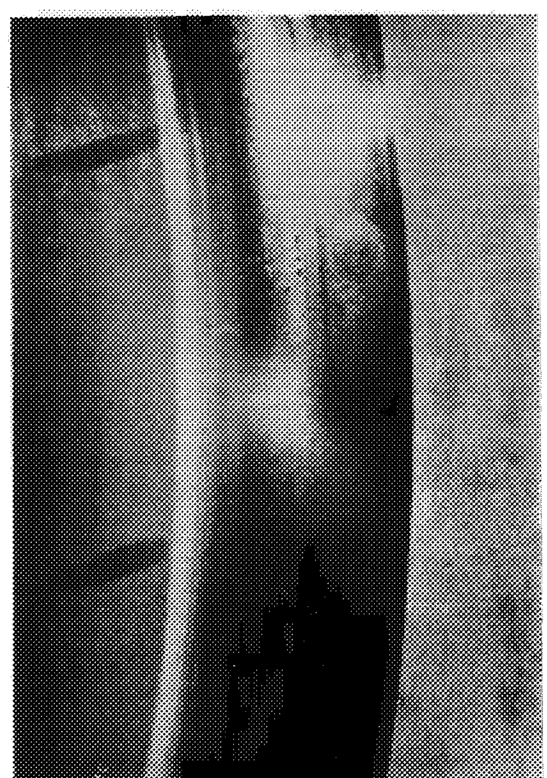
TEST BEARING #501 FROM TEST #5A USING DOW CORNING XF-1-0301

AFTER 100 HOURS AT 600°F





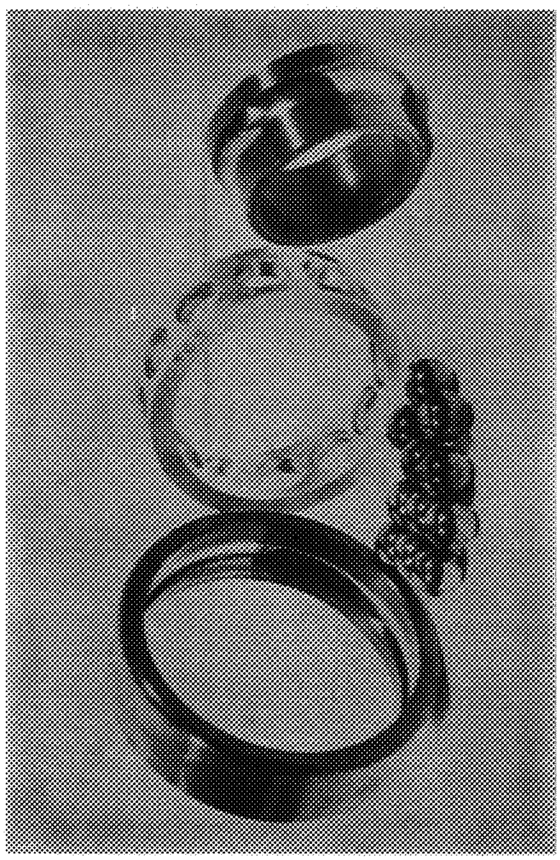
OUTER RACE

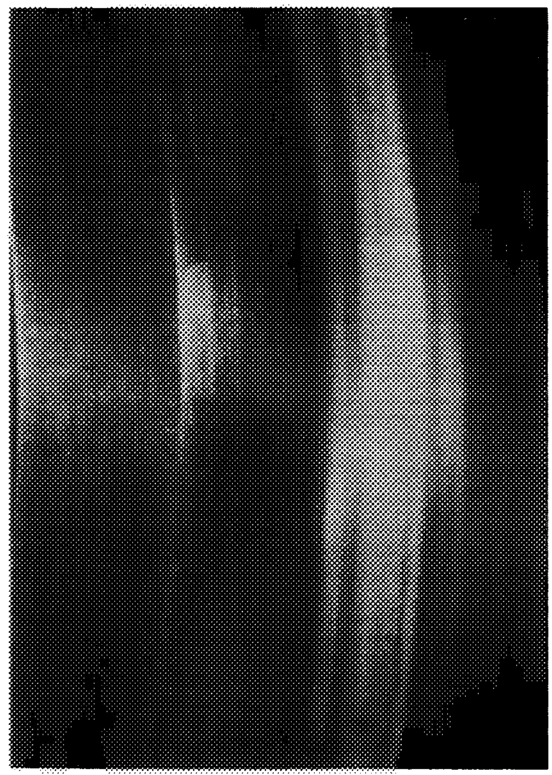


INNER RACE

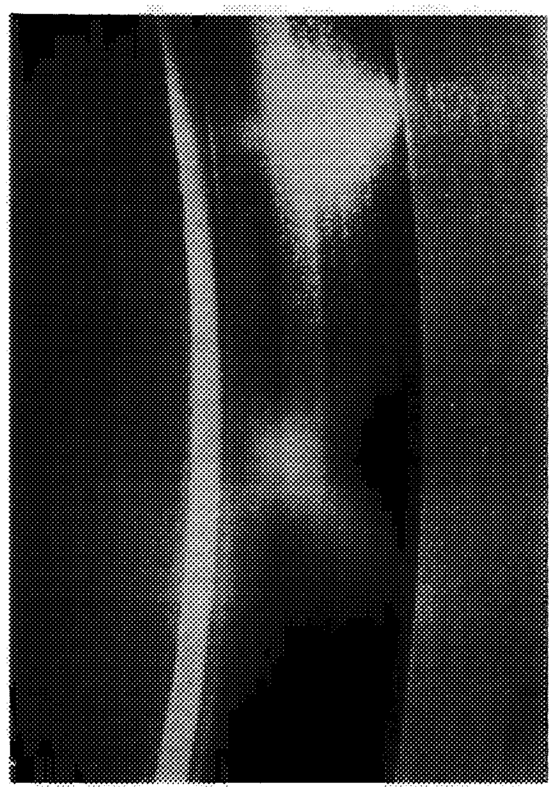
ENCLOSURE 33

TEST BEARING #503 FROM TEST #5B USING DOW CORNING XF-1-0301
AFTER 100 HOURS AT 600°F





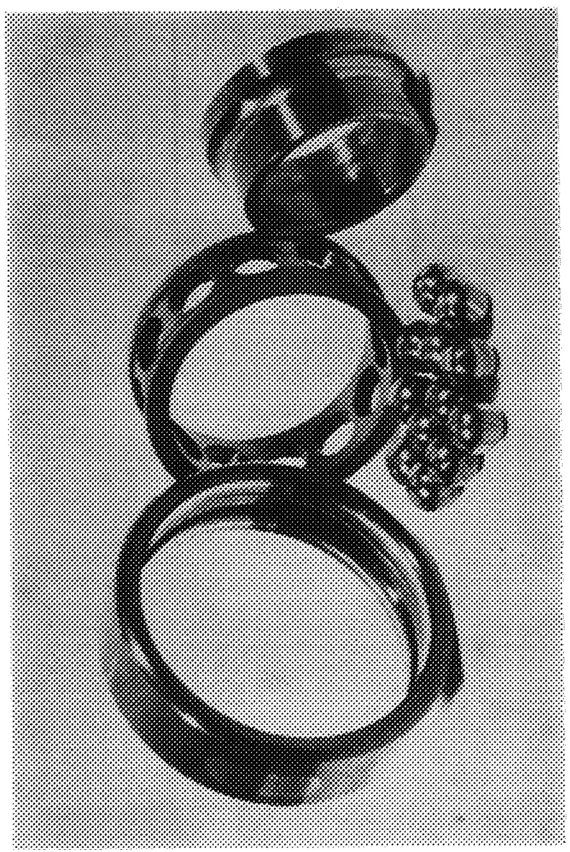
OUTER RACE

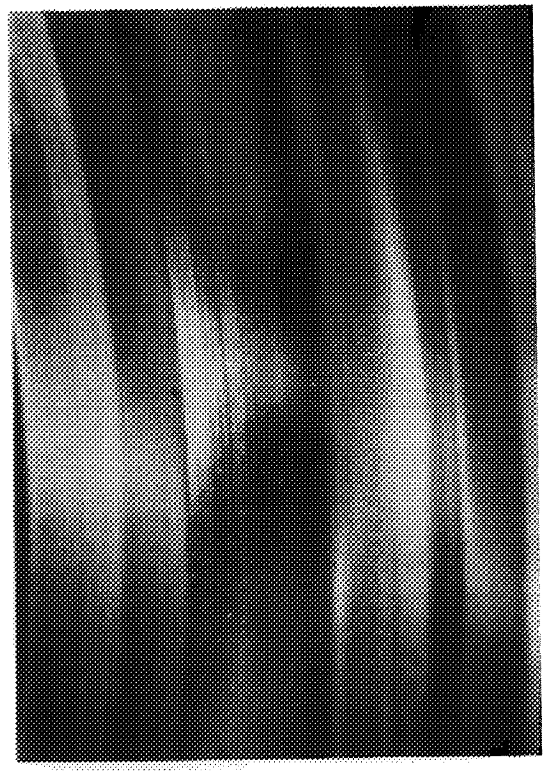


INNER RACE

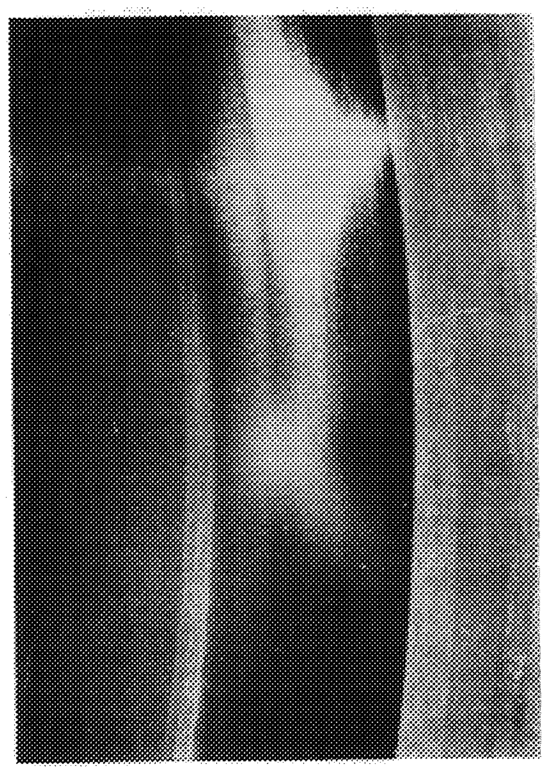
ENCLOSURE 34

TEST BEARING #505 FROM TEST #5C USING DOW CORNING XF-1-0301
AFTER 50 HOURS AT 600°F





OUTER RACE

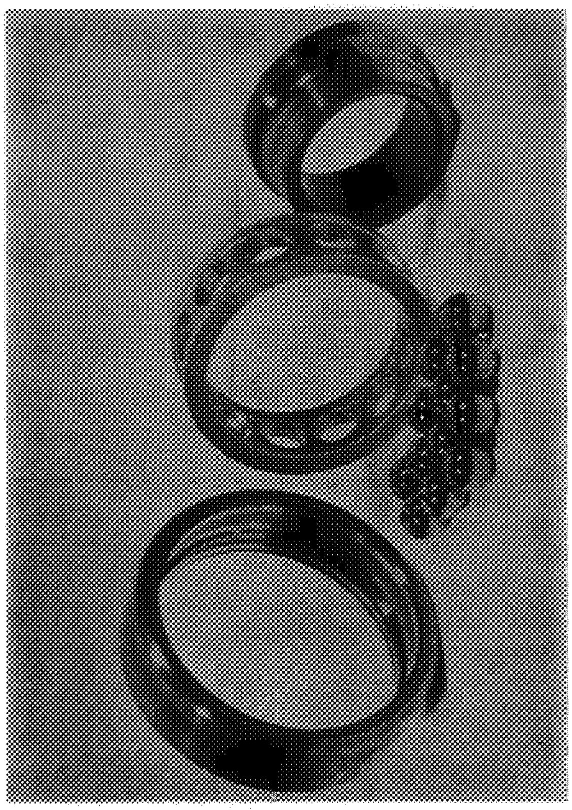


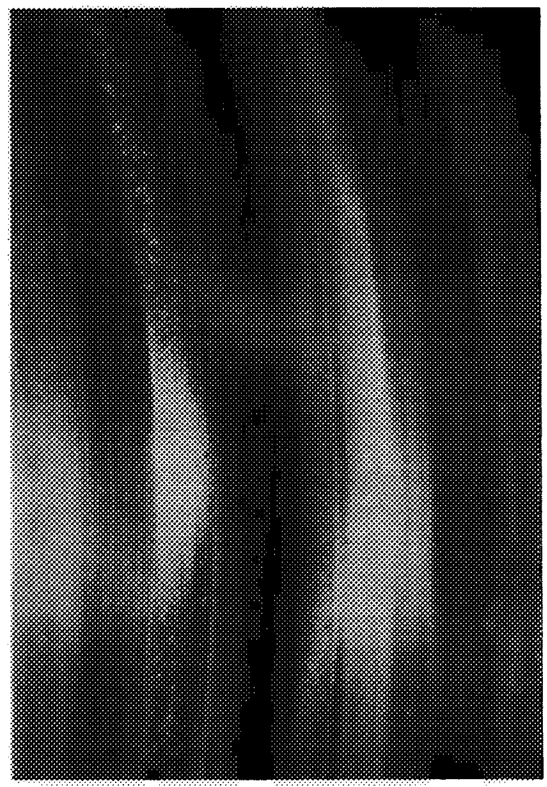
INNER RACE

ENCLOSURE 35

TEST BEARING #601 FROM TEST #6A USING MOBIL XRM-109F PLUS 10%
KENDALL RESIN

AFTER 100 HOURS AT 600°F



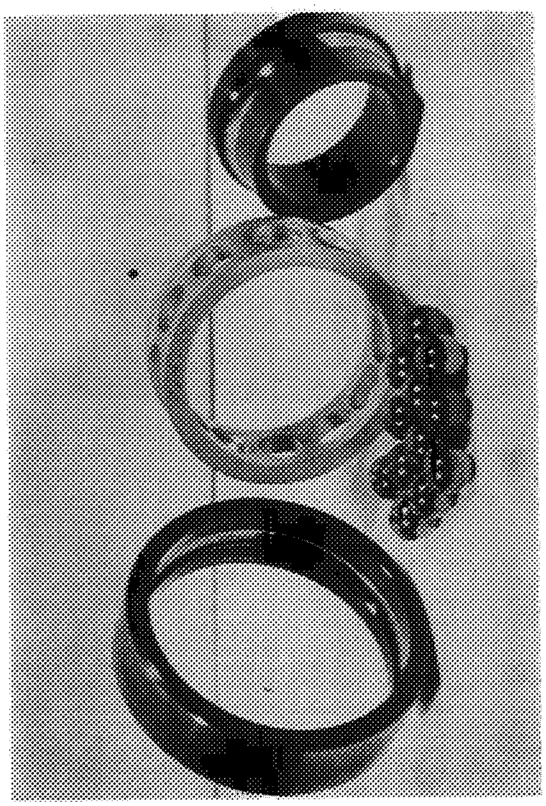


OUTER RACE

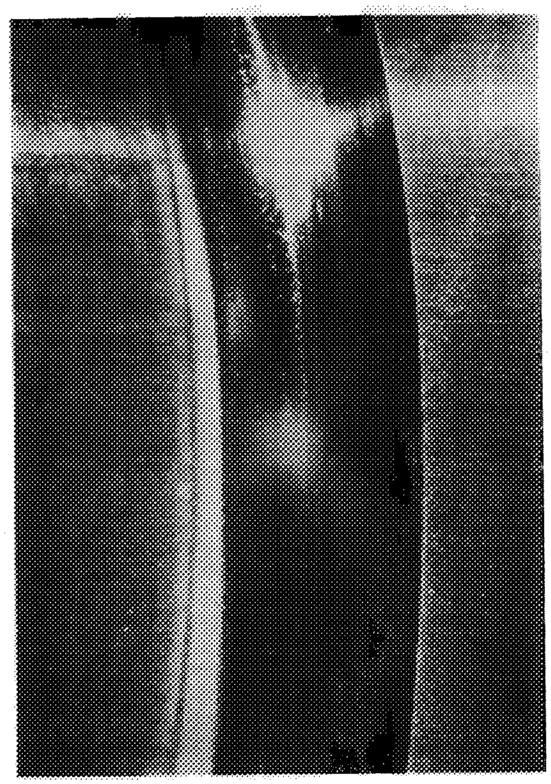
INNER RACE

ENCLOSURE 36

TEST BEARING #603 FROM TEST #6B USING MOBIL XRM-109F PLUS 10%
KENDALL RESIN
AFTER 100 HOURS AT 600°F



OUTER RACE

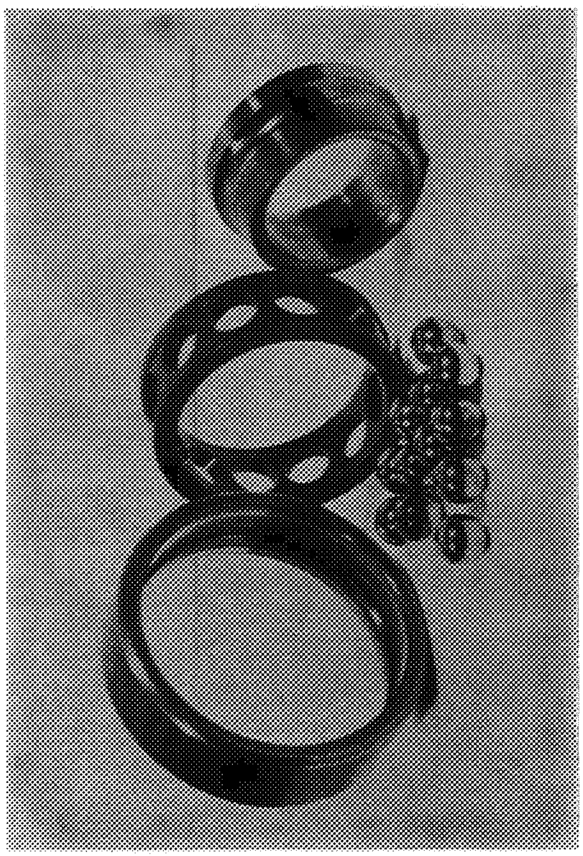


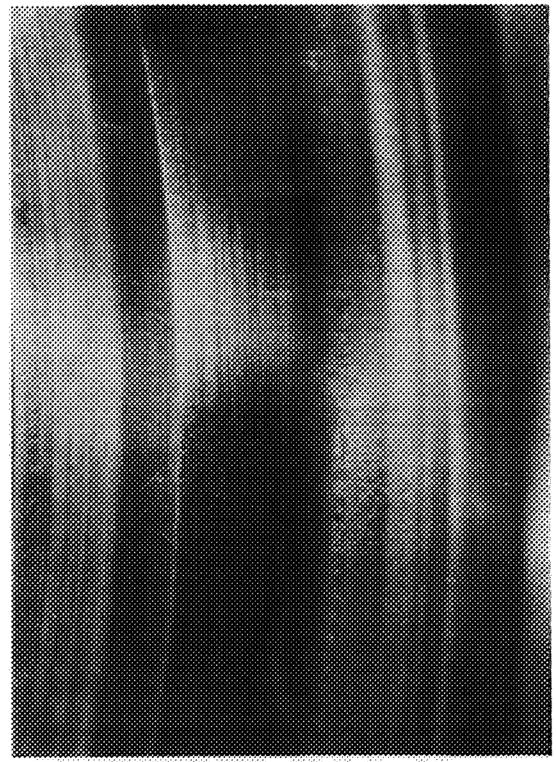
INNER RACE

ENCLOSURE 37

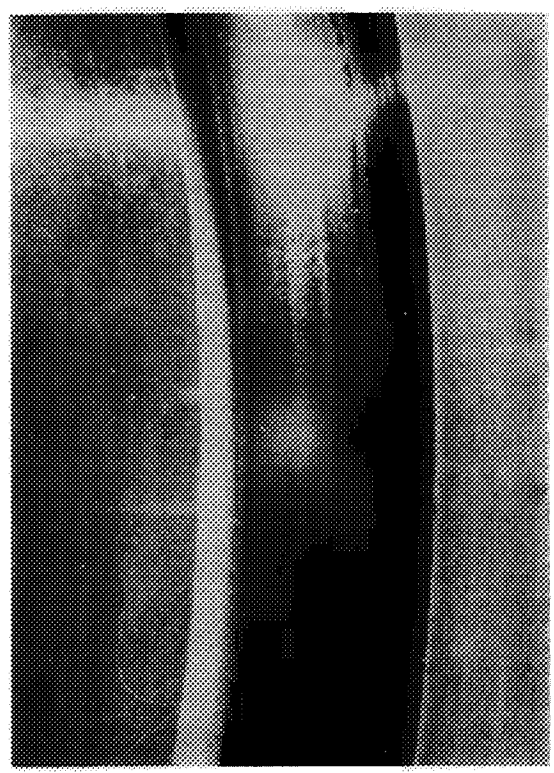
TEST BEARING #605 FROM TEST #6C USING MOBIL XRM-109F PLUS 10%
KENDALL RESIN

AFTER 50 HOURS AT 600°F





OUTER RACE

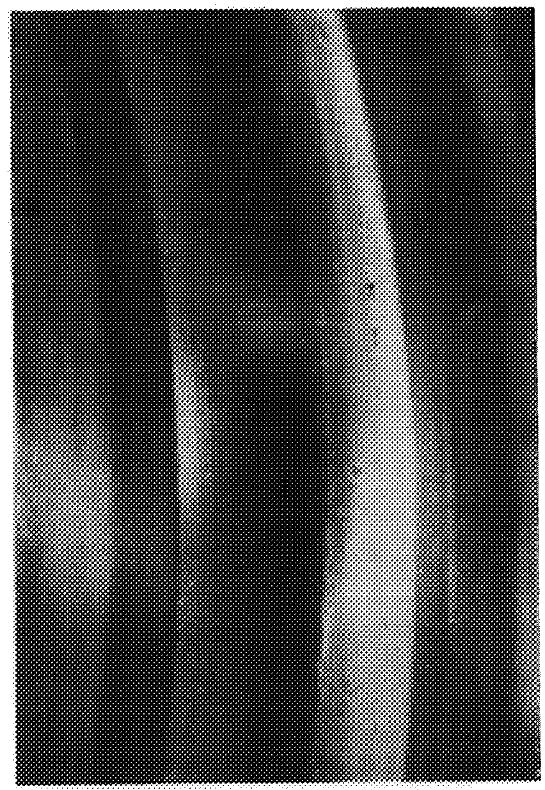


INNER RACE

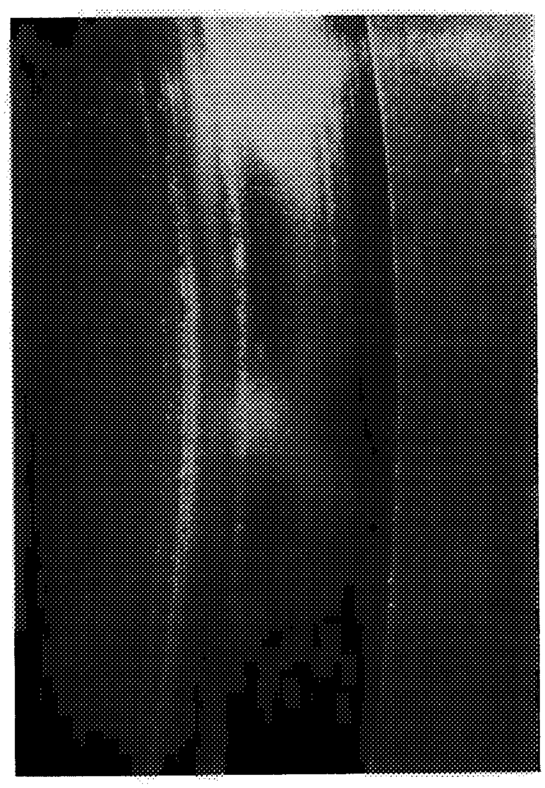
ENCLOSURE 38

TEST BEARING #701 FROM TEST #7A USING ESSO AL07873

AFTER 100 HOURS AT 600°F



OUTER RACE

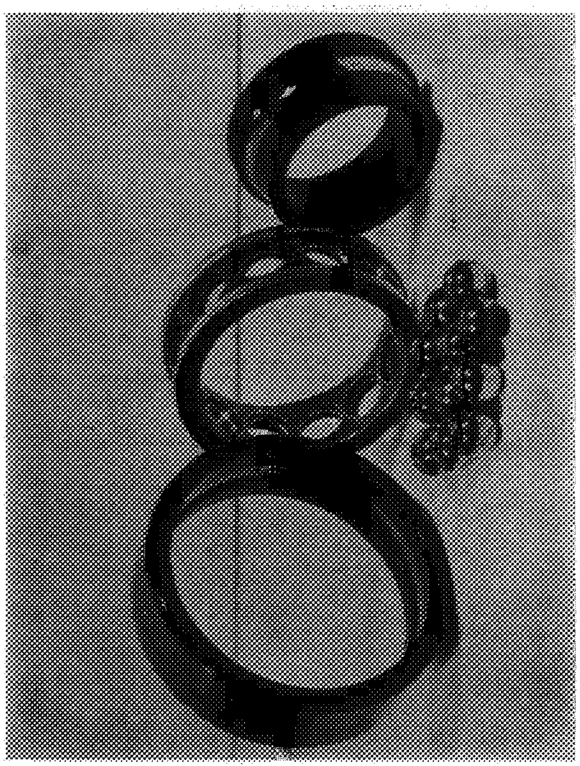


INNER RACE

ENCLOSURE 39

TEST BEARING #703 FROM TEST #7B USING ESSO AL07873
AFTER 100 HOURS AT 600°F

OUTER RACE

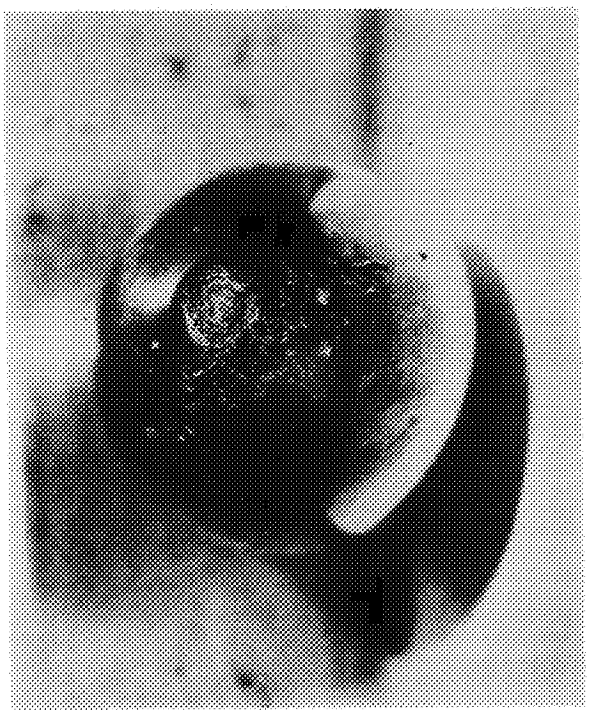


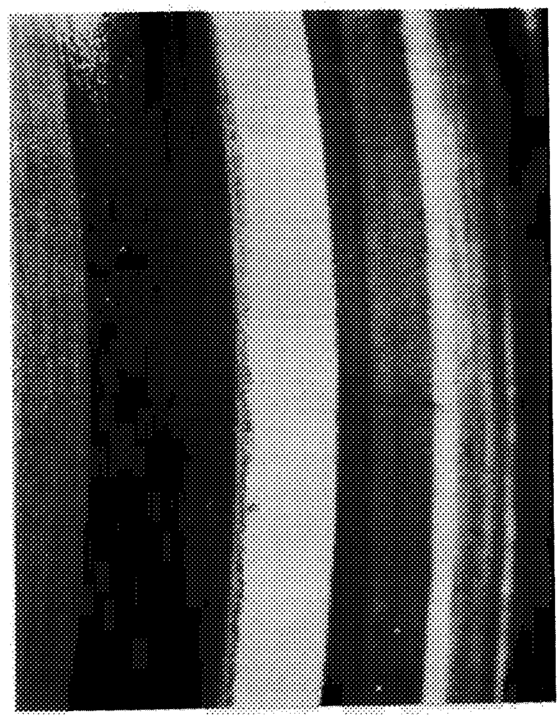
INNER RACE

ENCLOSURE 40

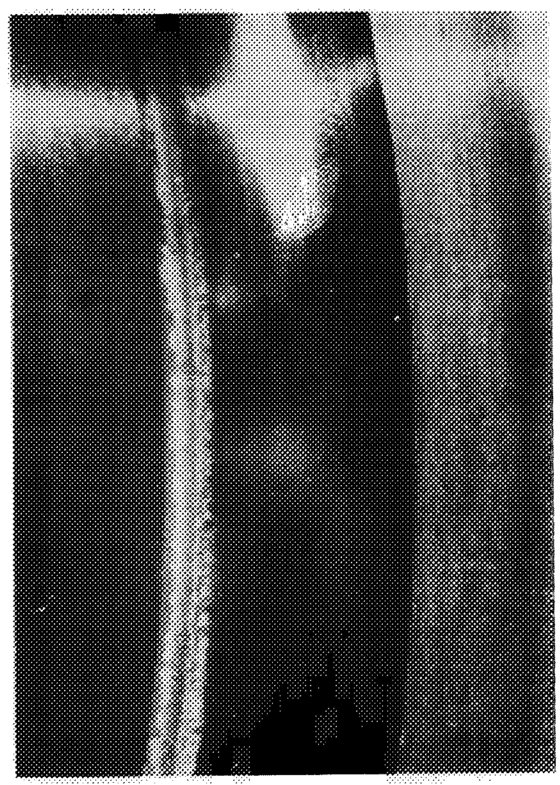
TEST BEARING #705 FROM TEST #7C USING ESSO AL07873

AFTER 50 HOURS AT 600°F





OUTER RACE

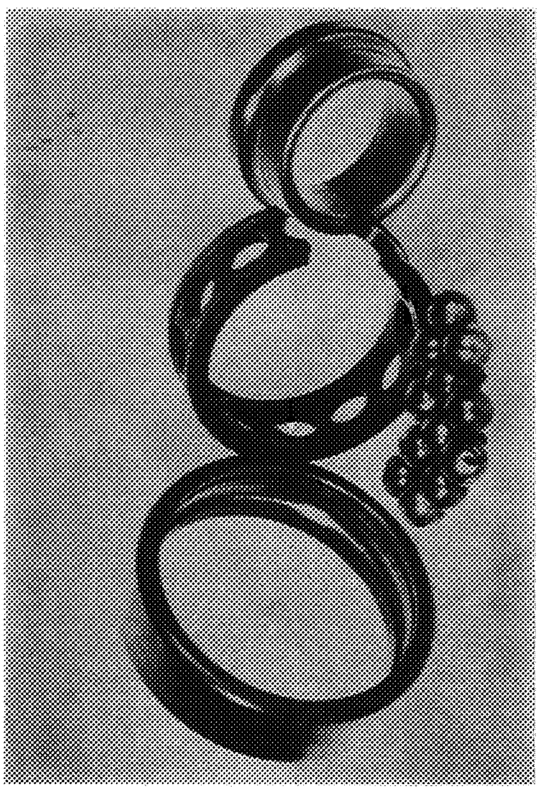


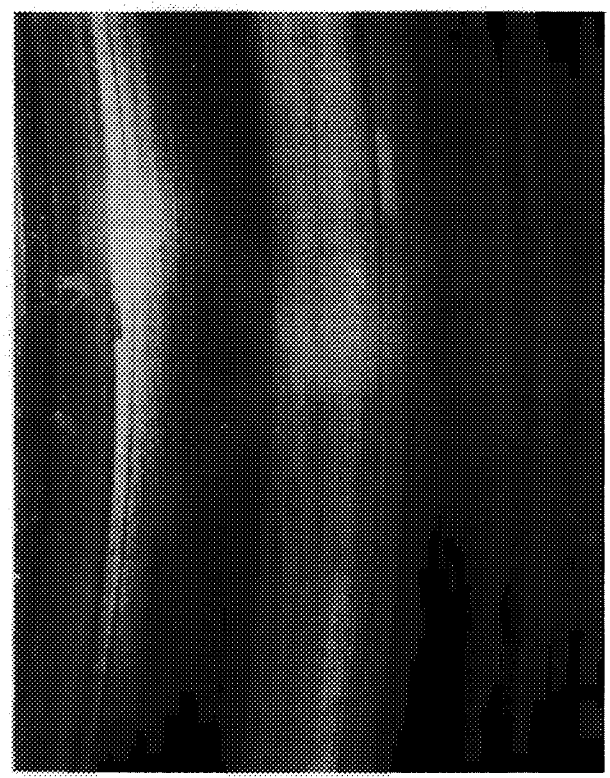
INNER RACE

**ENCLOSURE 41**

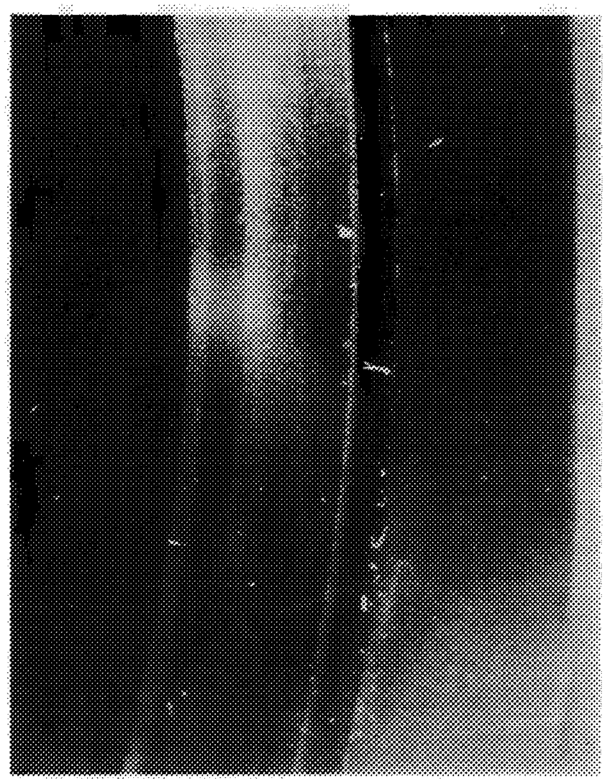
TEST BEARING #805 FROM TEST #8C USING DuPONT KRYTOX 143 AB

AFTER 50 HOURS AT 600°F





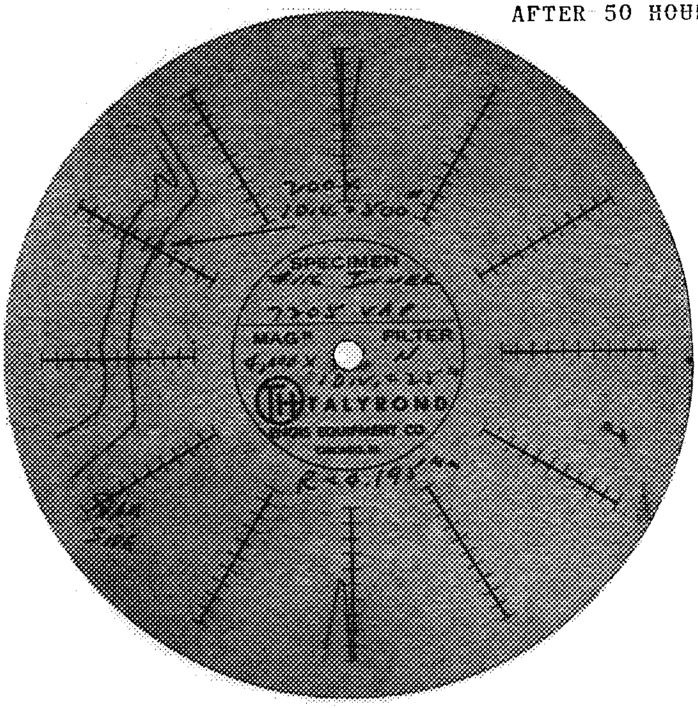
OUTER RACE



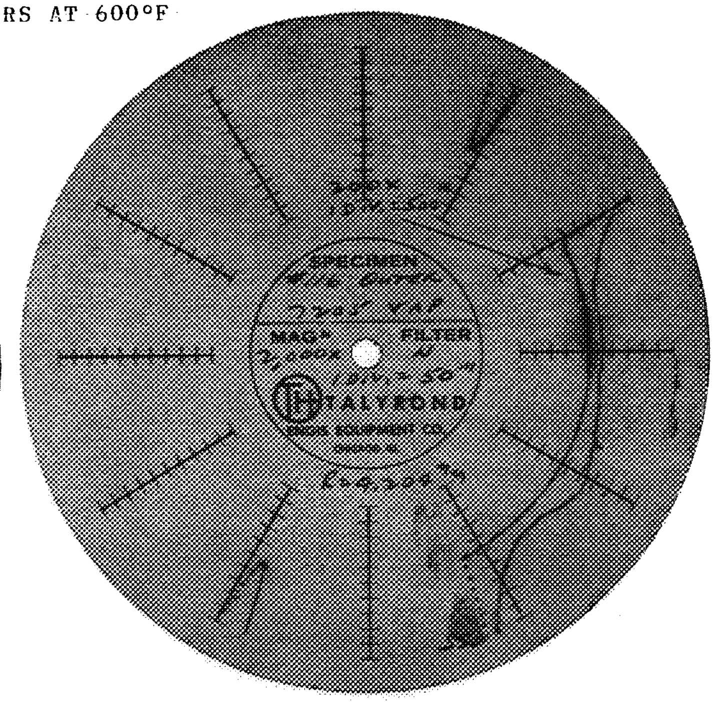
INNER RACE

ENCLOSURE 42

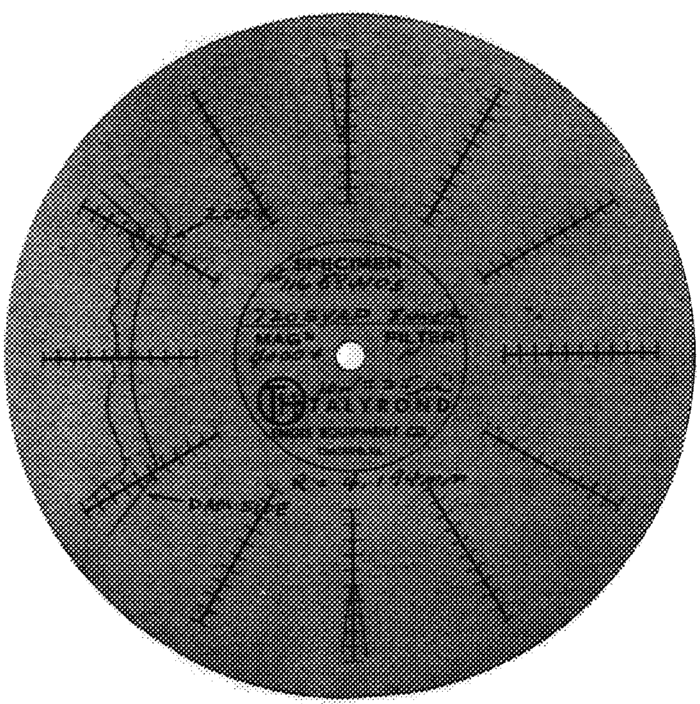
TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #105 FROM TEST#1C USING MOBIL XRM-109F
AFTER 50 HOURS AT 600°F



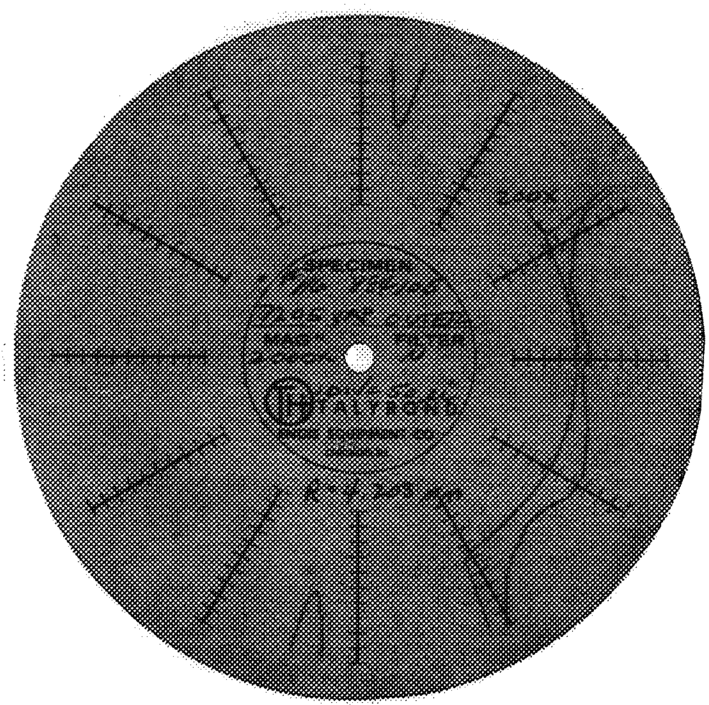
BEFORE



BEFORE



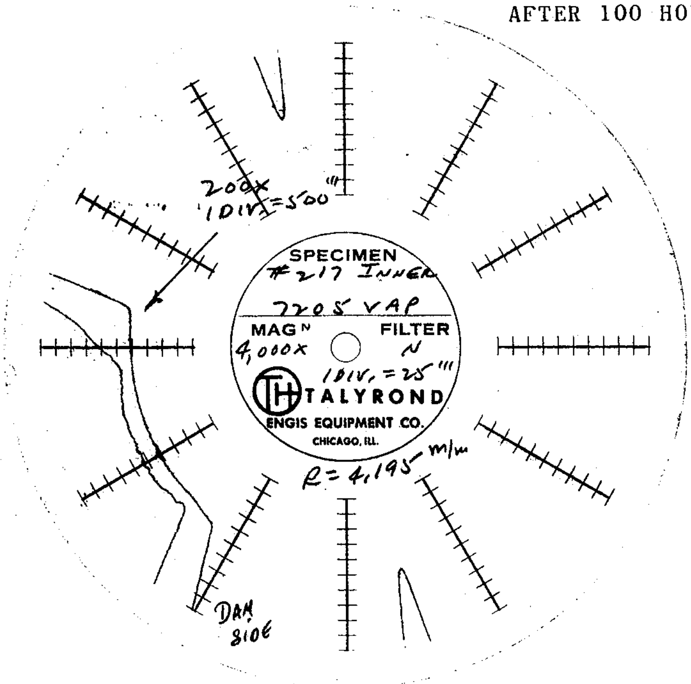
AFTER



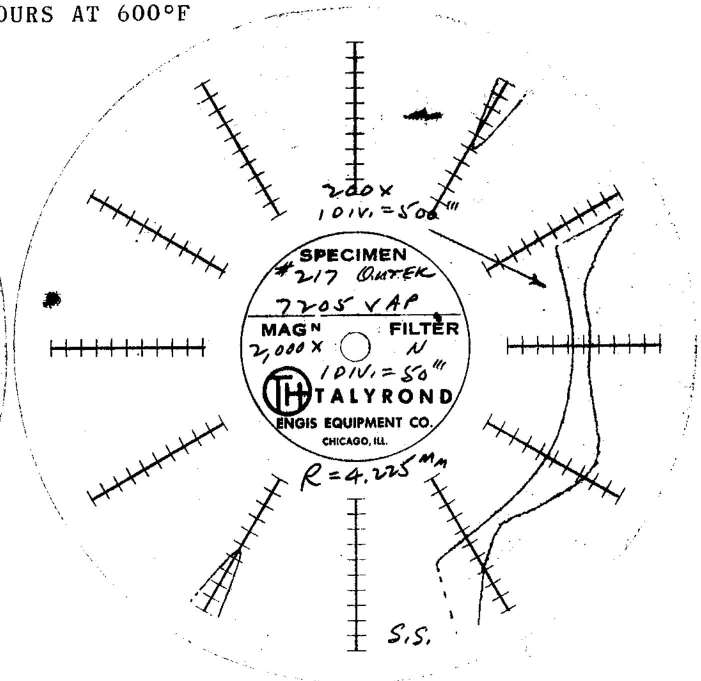
AFTER

ENCLOSURE 43

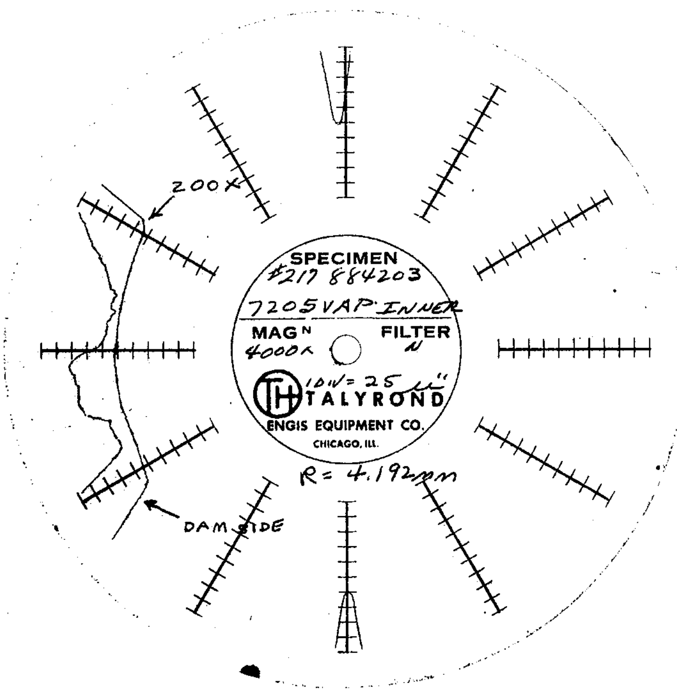
TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #203 FROM TEST# 2B USING MONSANTO MCS-2931
AFTER 100 HOURS AT 600°F



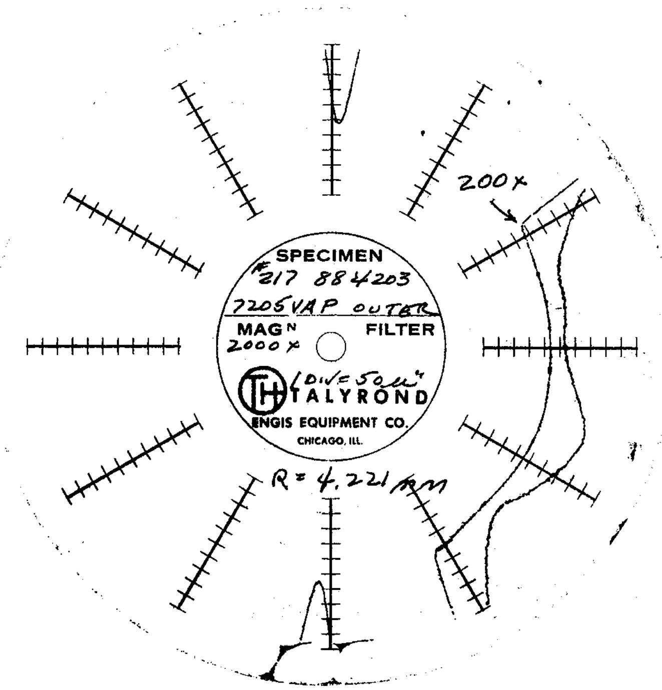

BEFORE




BEFORE




AFTER




AFTER

Bind

F4186A - R80 - 10.62 X 13.75

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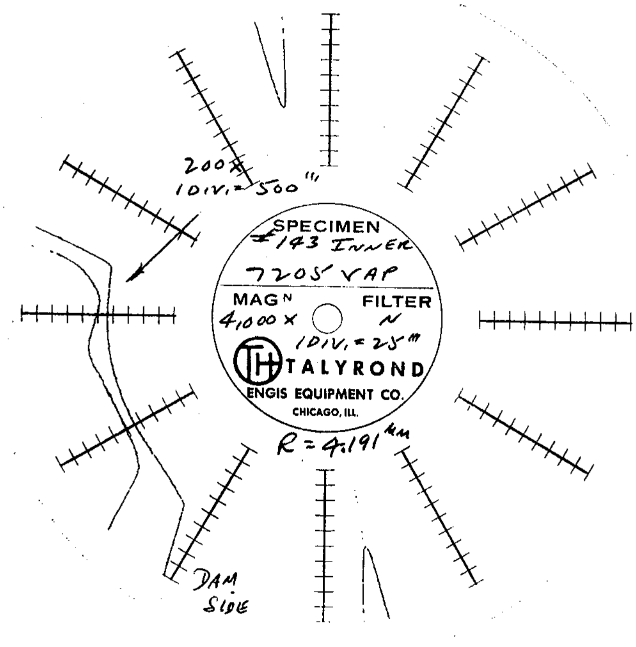
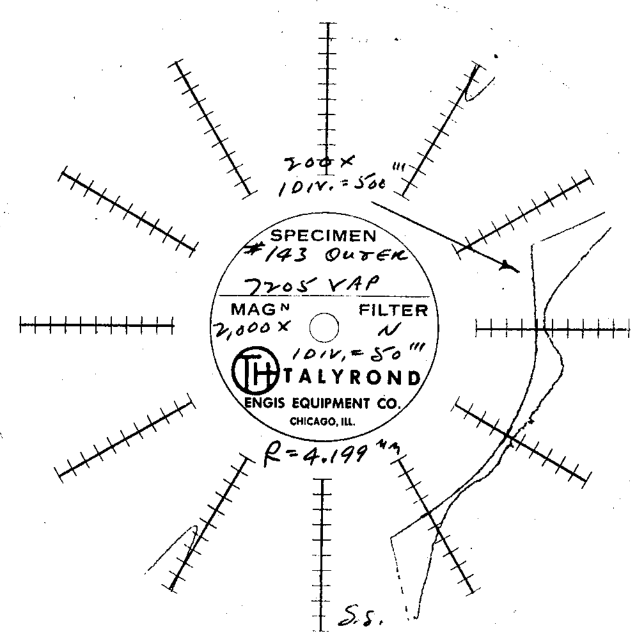
ENCLOSURE 44

TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #303 FROM TEST #3B USING HUMBLE FN-3158

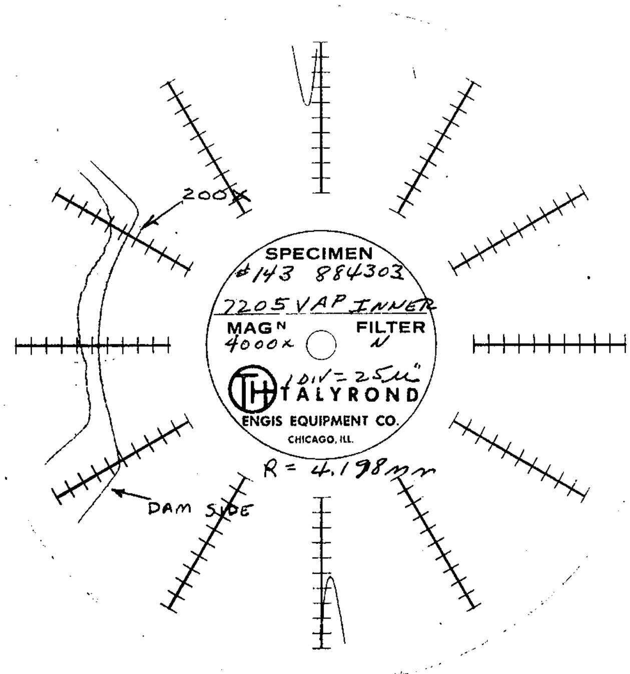
AFTER 40.3 HOURS AT 600°F



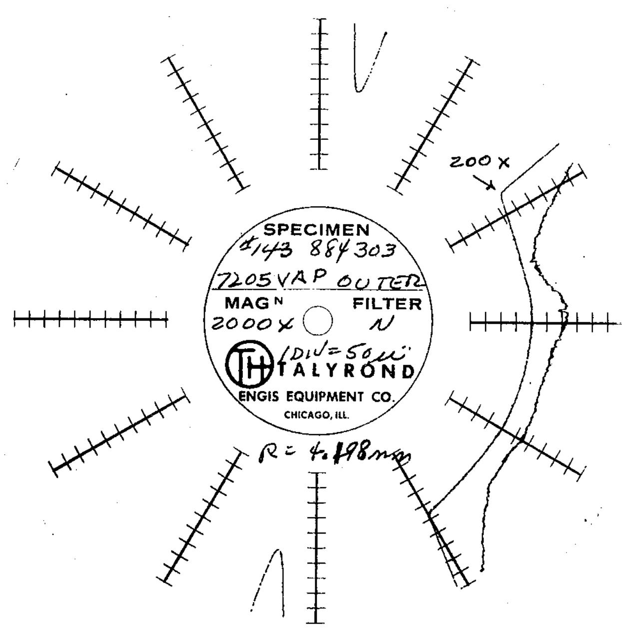

BEFORE




BEFORE



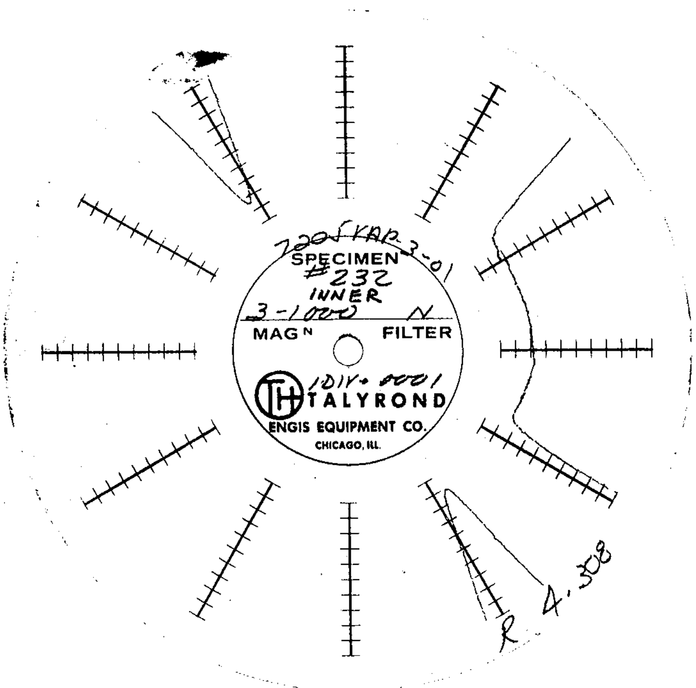

AFTER



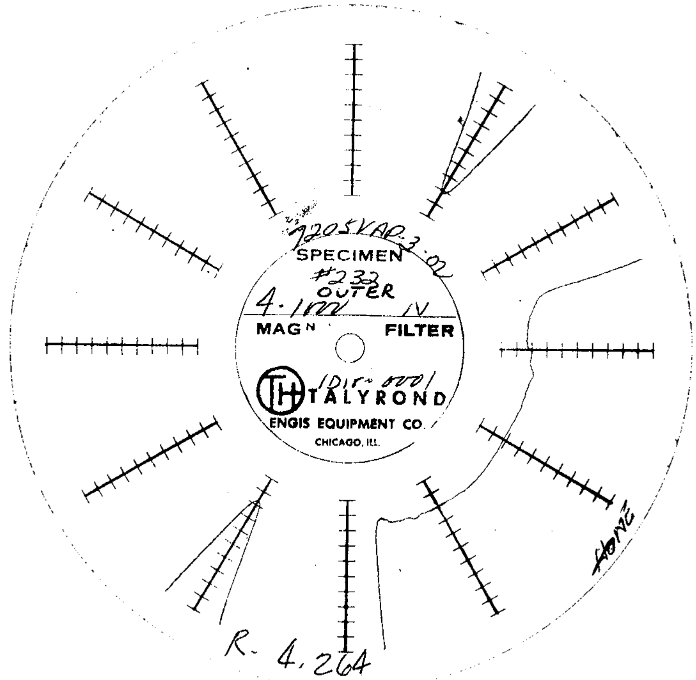

AFTER

ENCLOSURE 45

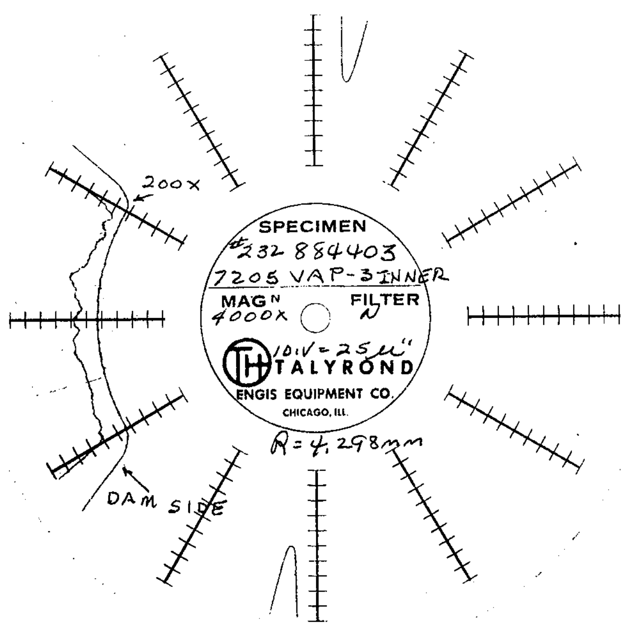
TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #403 FROM TEST #4B USING HUMBLE FN-3158 PLUS 10% KENDALL RESIN AFTER 100 HOURS AT 600°F



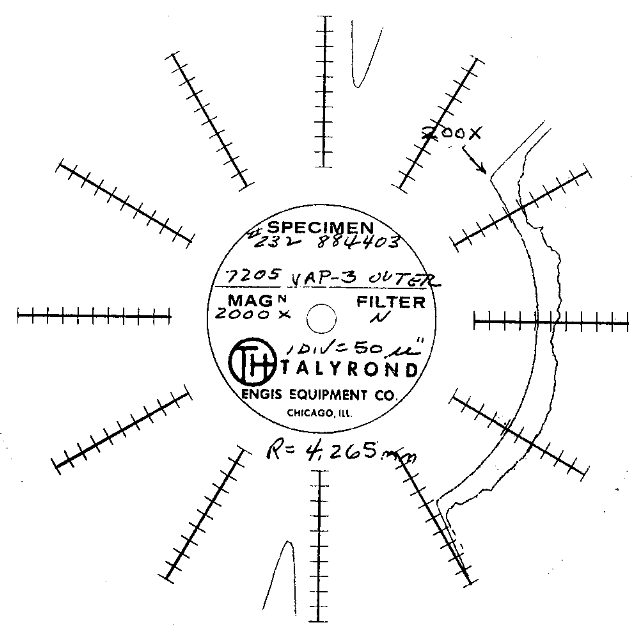

BEFORE




BEFORE




AFTER




AFTER

Bind

F4186A - R80 - 10.62 X 13.75

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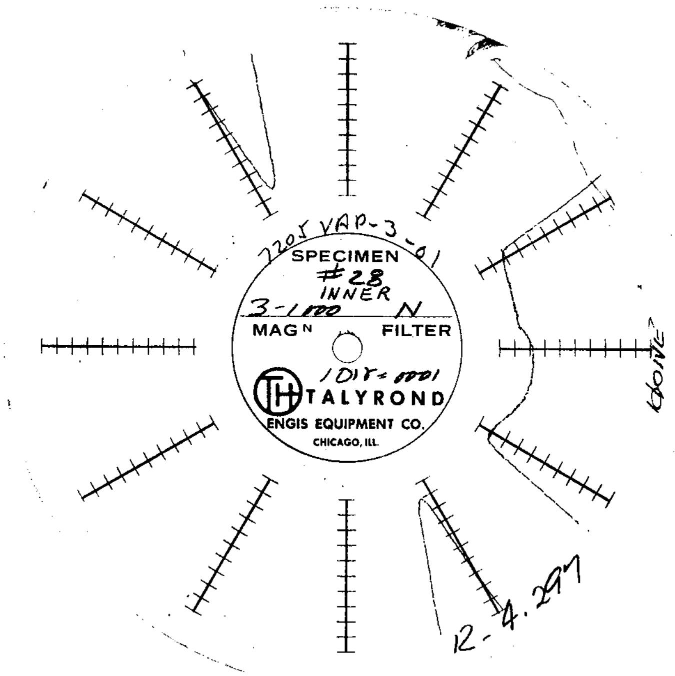
# ENCLOSURE 46

TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #501 FROM TEST# 5A USING DOW CORNING XF-1-0301
AFTER 100 HOURS AT 600°F

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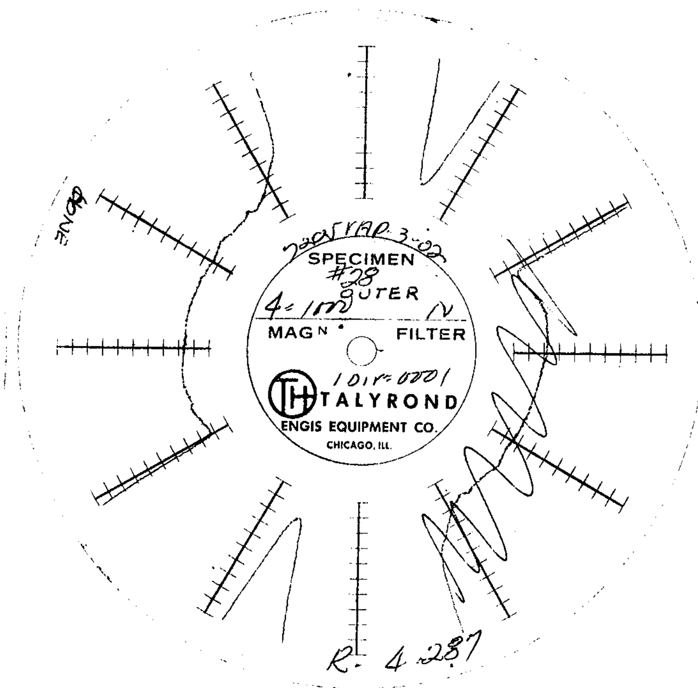


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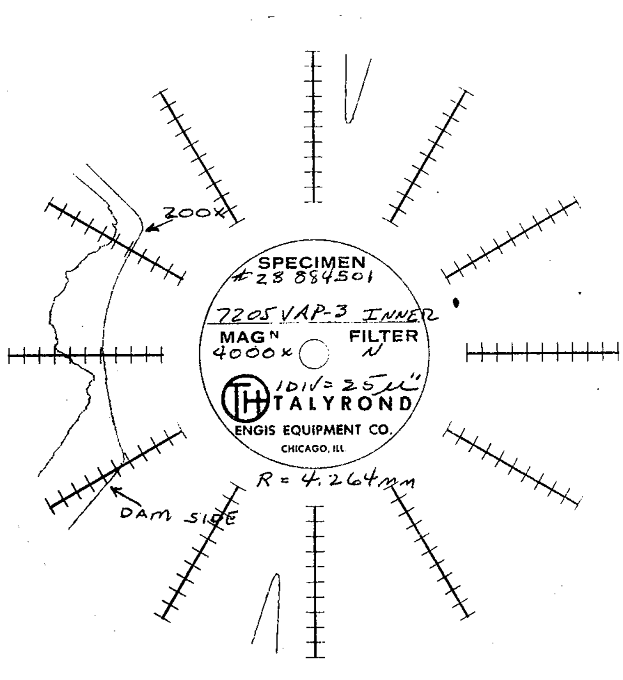


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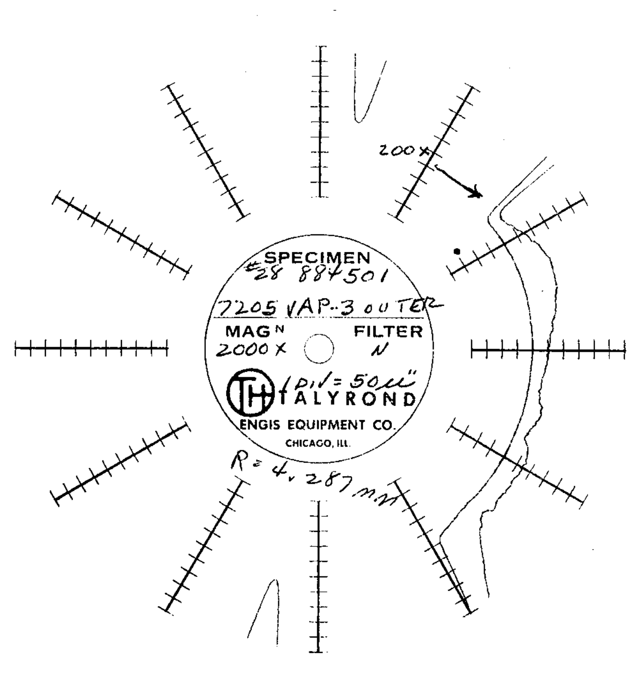
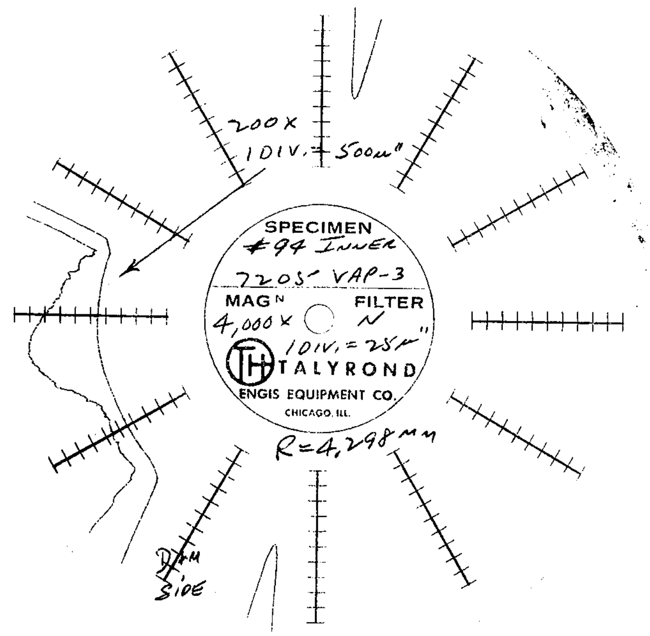



AFTER

# ENCLOSURE 47

TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #601 FROM TEST#6A USING MOBIL XRM-109F PLUS 10% KENDALL RESIN

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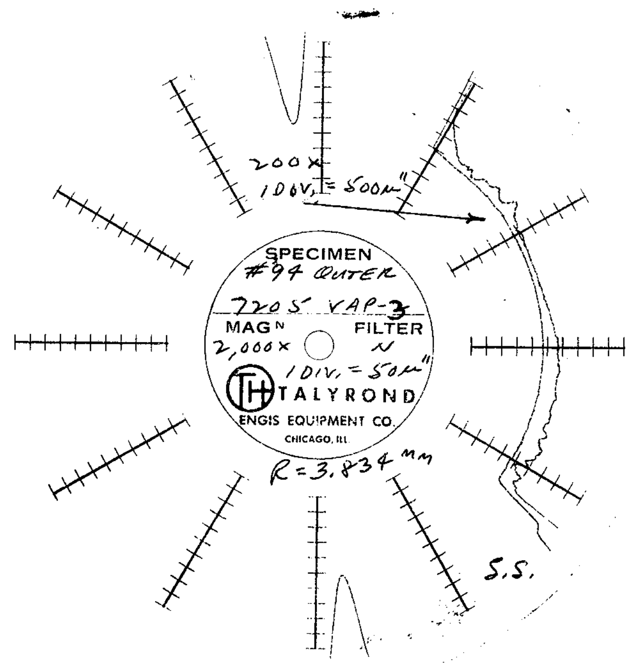


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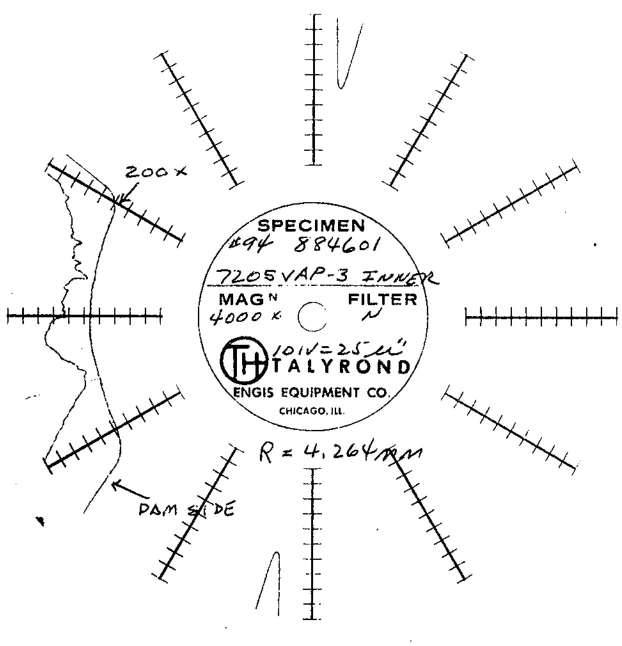


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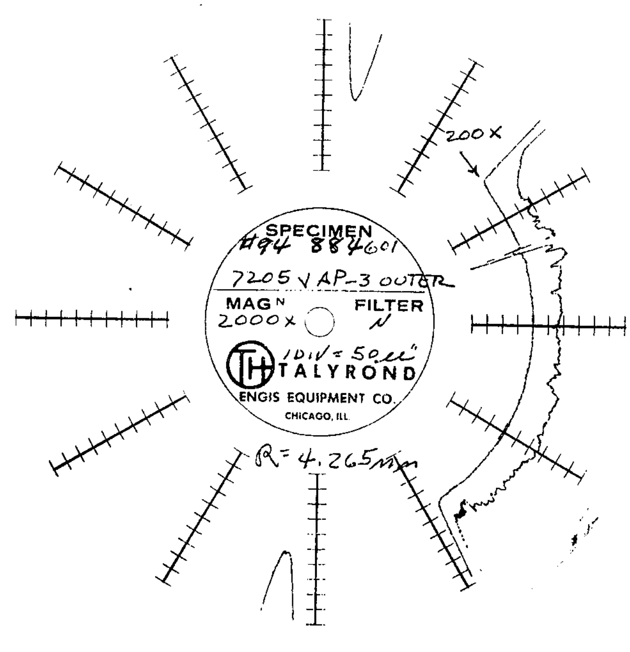
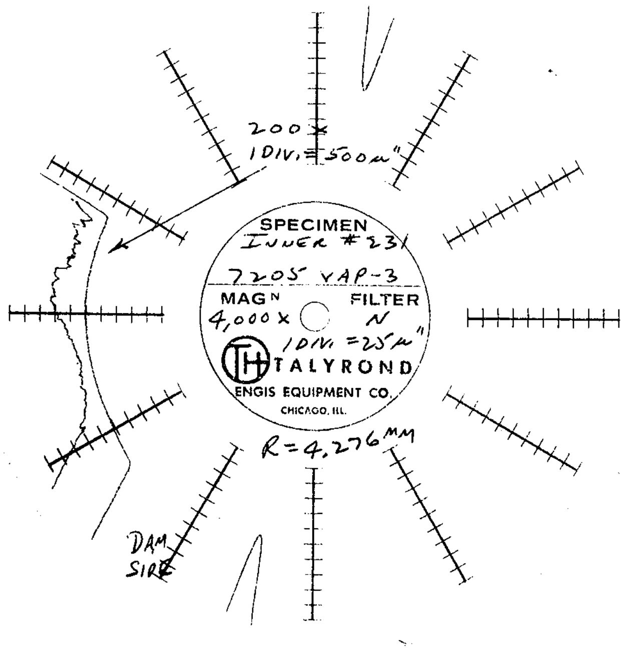



AFTER

ENCLOSURE 48

TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #701 FROM TEST#7A USING ESSO AL07873
AFTER 100 HOURS AT 600°F

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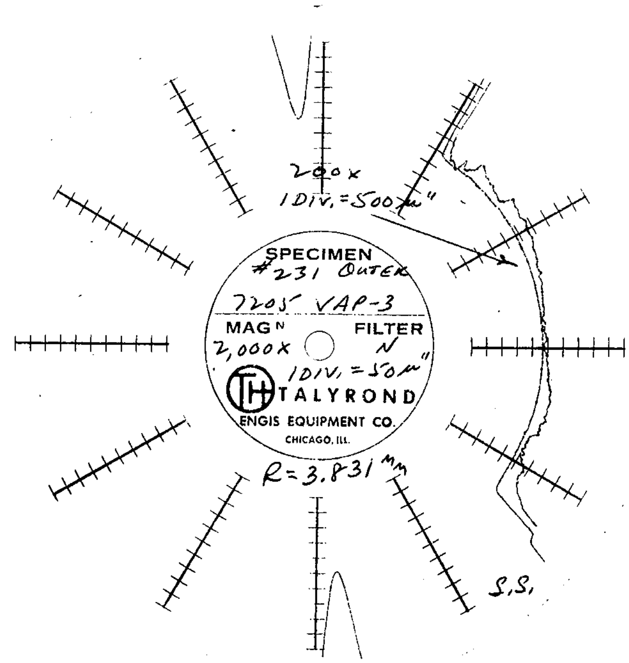


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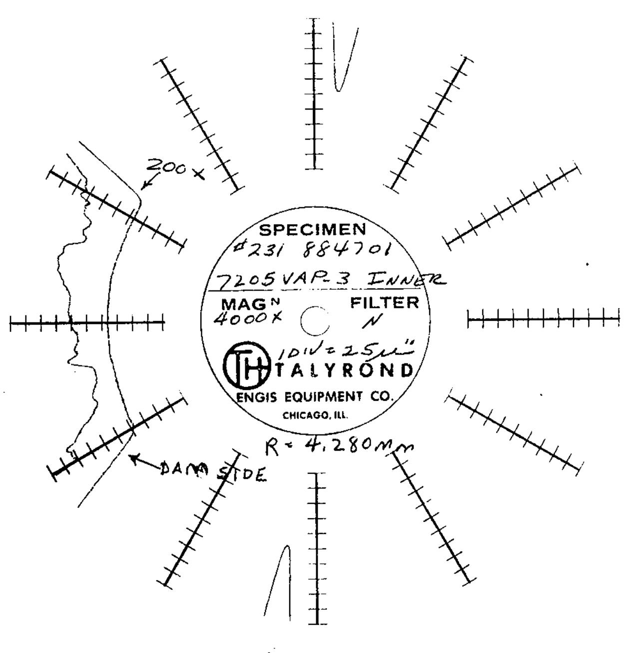


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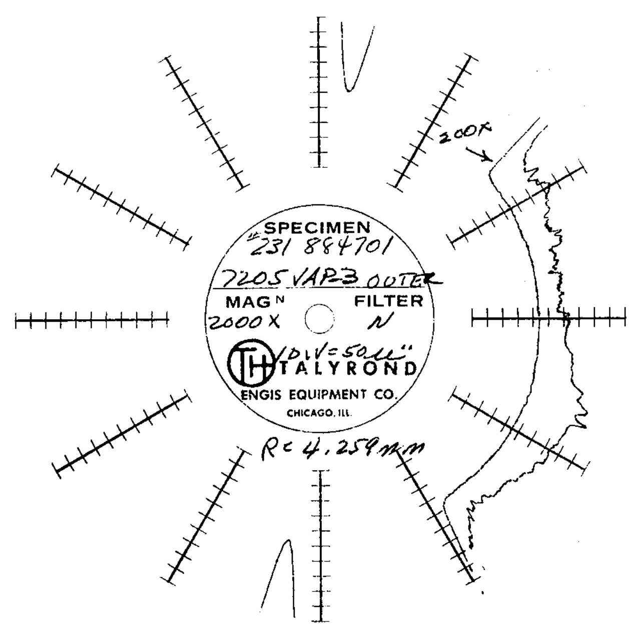
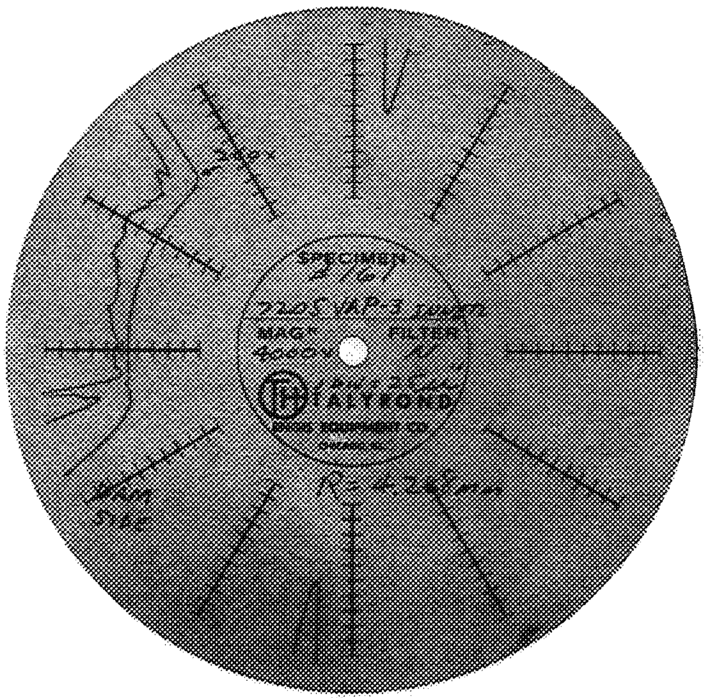



AFTER

F4186A - R80 - 10.62 X 13.75

ENCLOSURE 49

TALYROND TRACES BEFORE AND AFTER TESTING FOR TEST BEARING #805 FROM TEST #8C USING DUPont Krytox 143AB AFTER 50 HOURS AT 600°F

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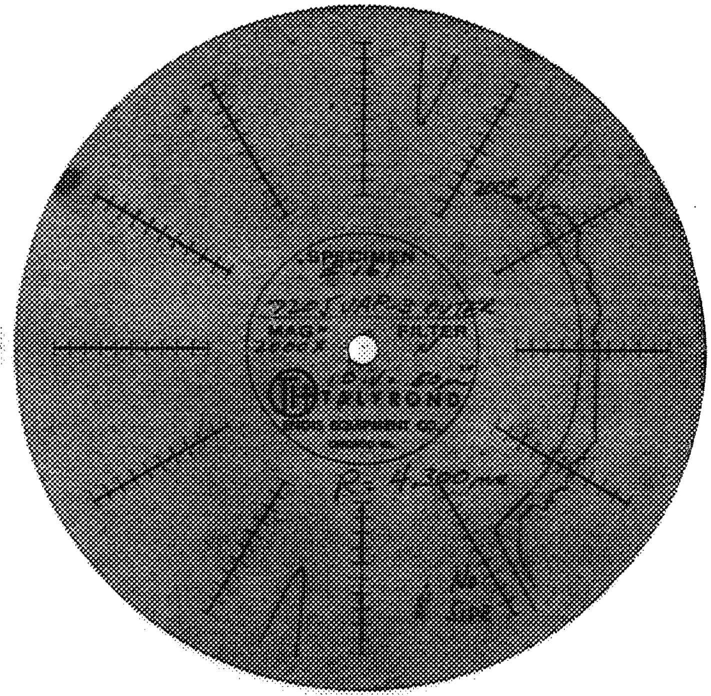


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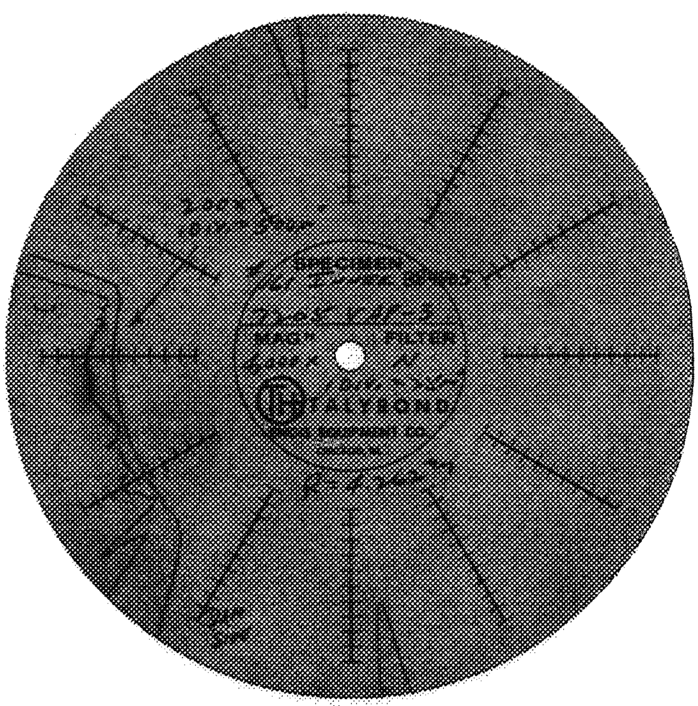


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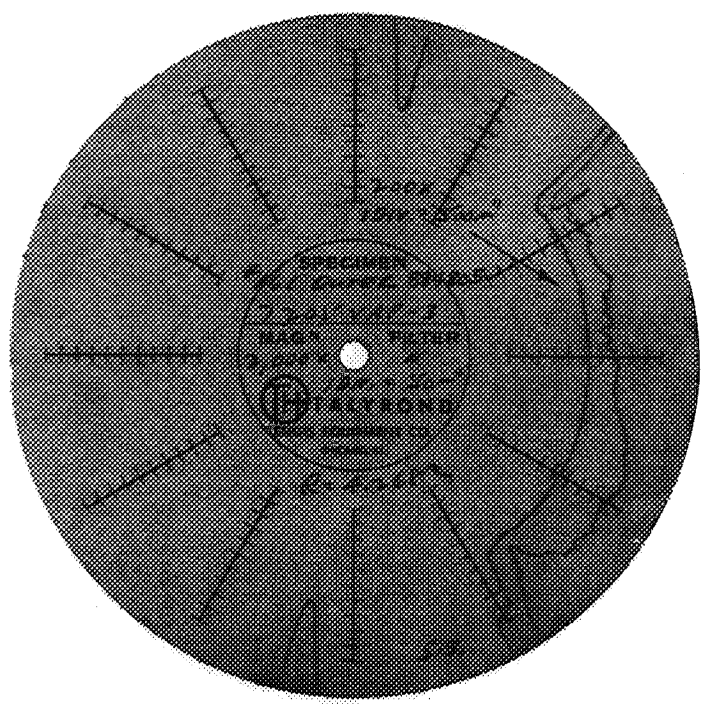
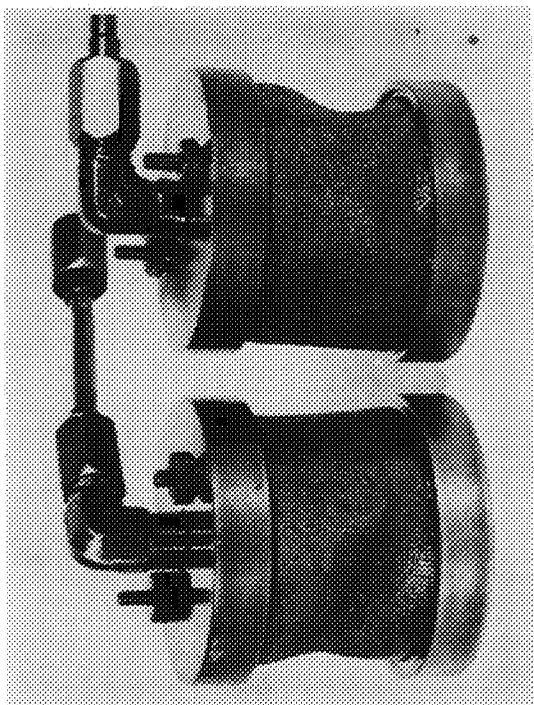


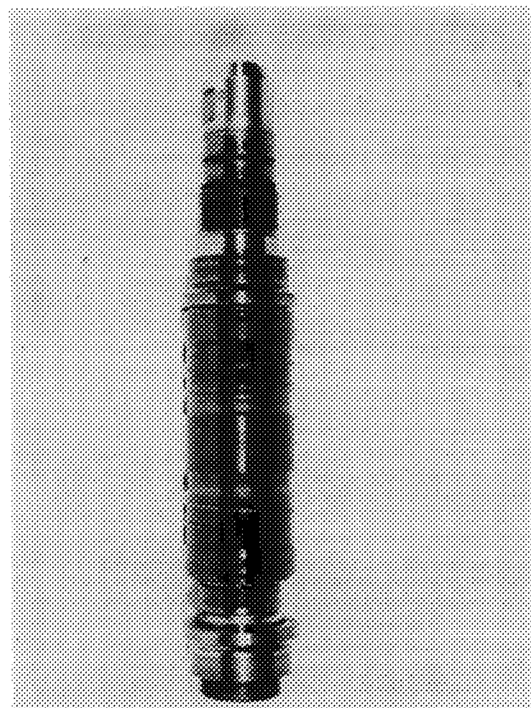

AFTER

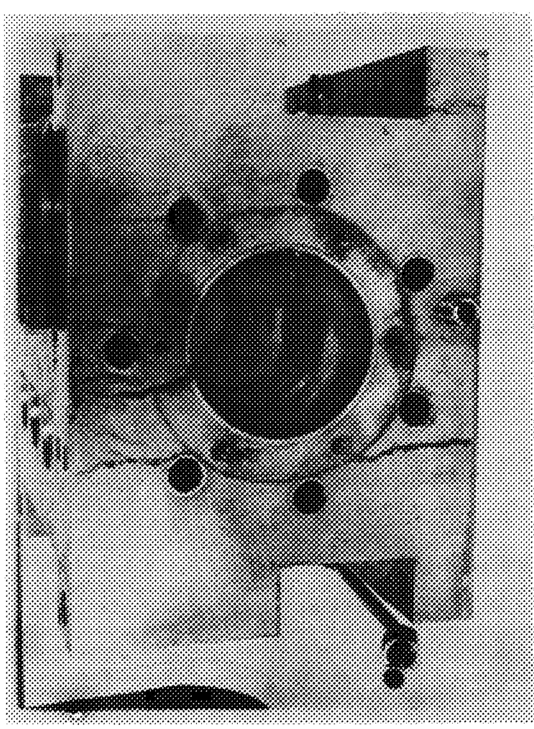
ENCLOSURE 50

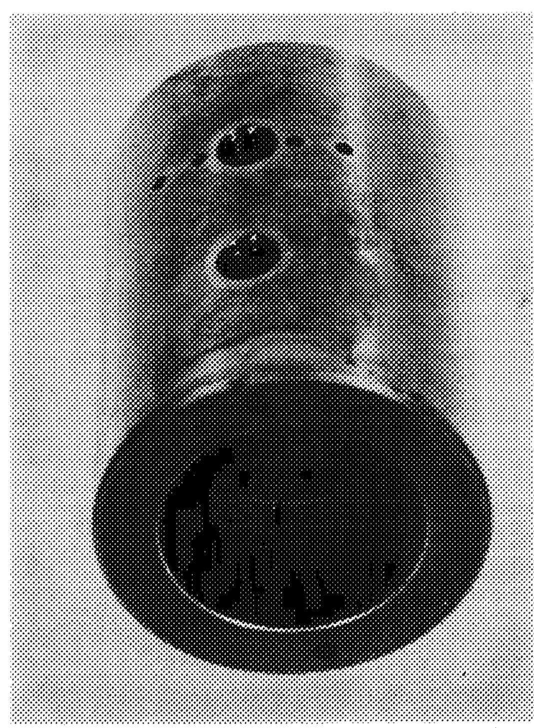
OIL FILTERS, TEST SHAFT, BEARING HOUSINGS, AND SHAFT LINER FROM TEST #2B USING MONSANTO MCS-2931

AFTER 100 HOURS AT 600°F





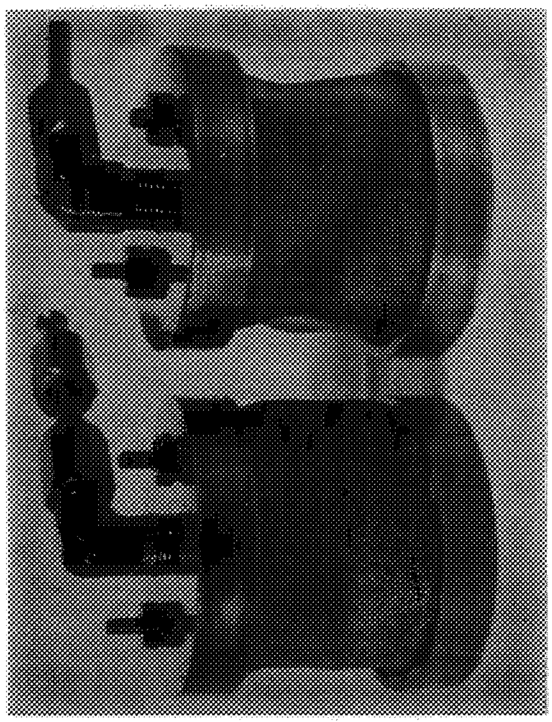


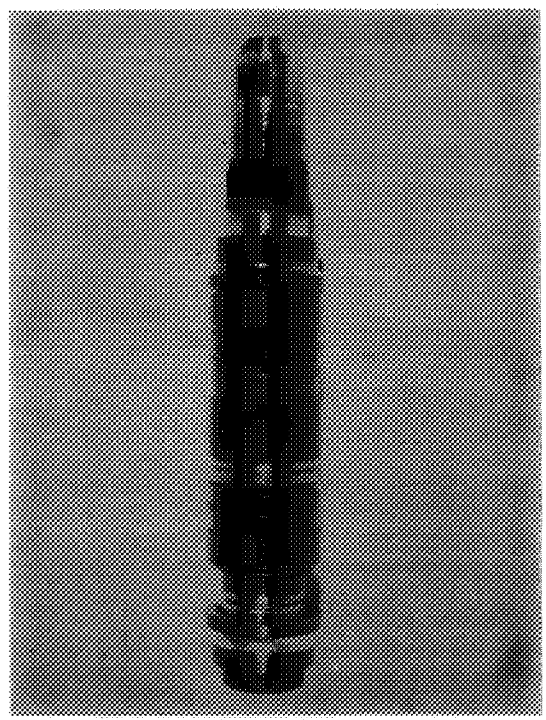


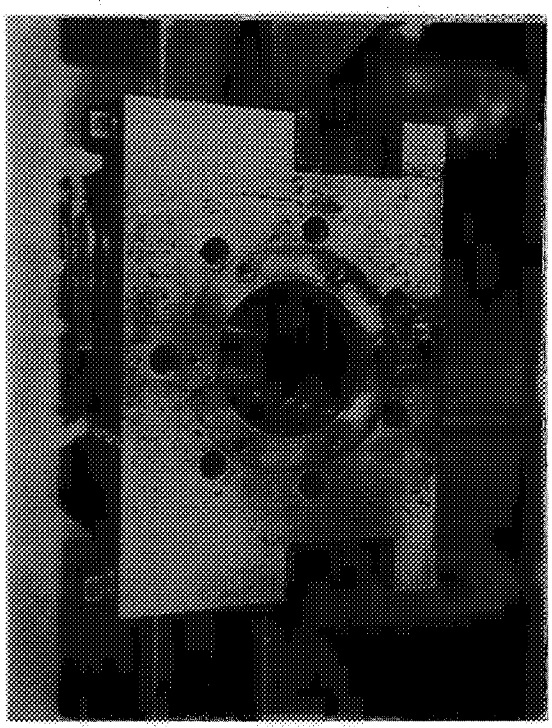
ENCLOSURE 51

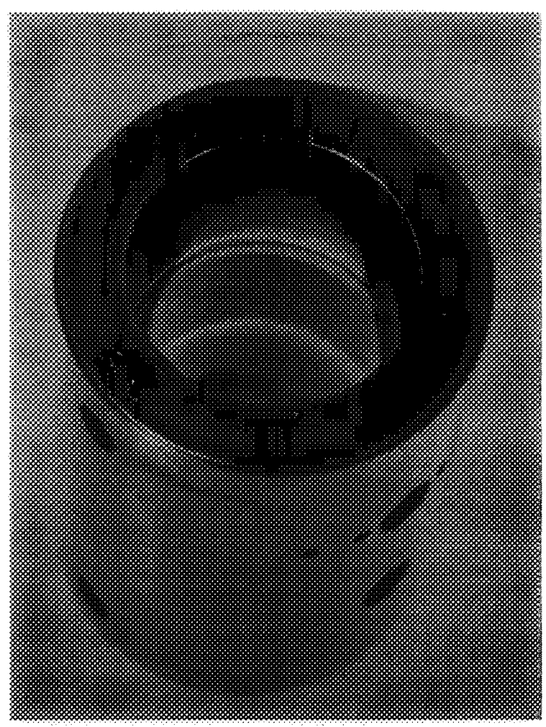
OIL FILTERS, TEST SHAFT, BEARING HOUSINGS, AND SHAFT LINER FROM TEST #3A USING HUMBLE FN-3158

AFTER 71.1 HOURS AT 600°F





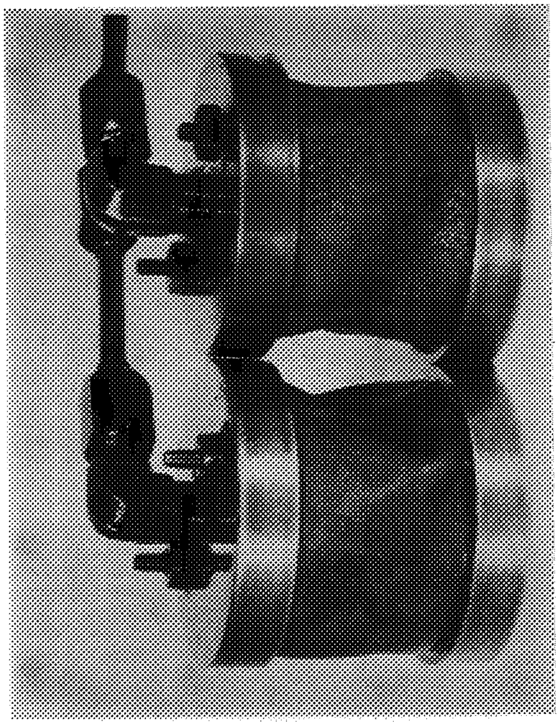


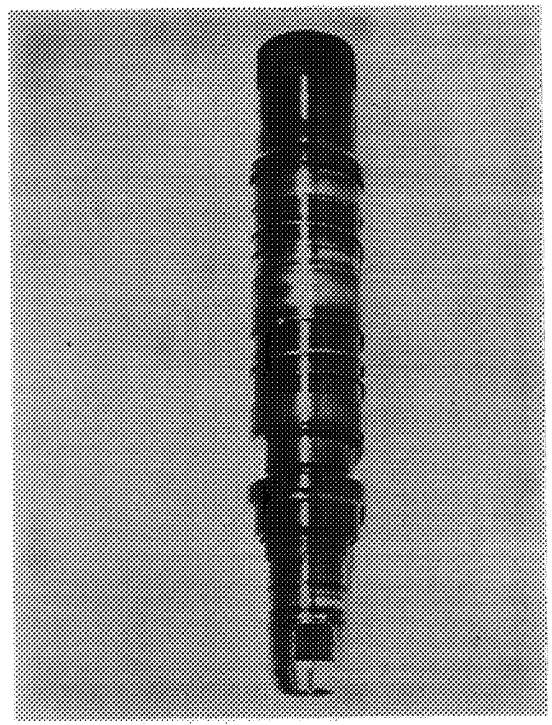


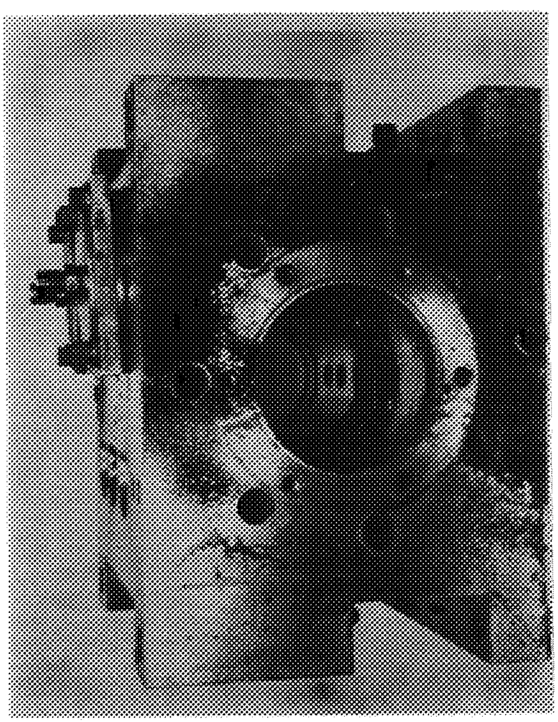
ENCLOSURE 52

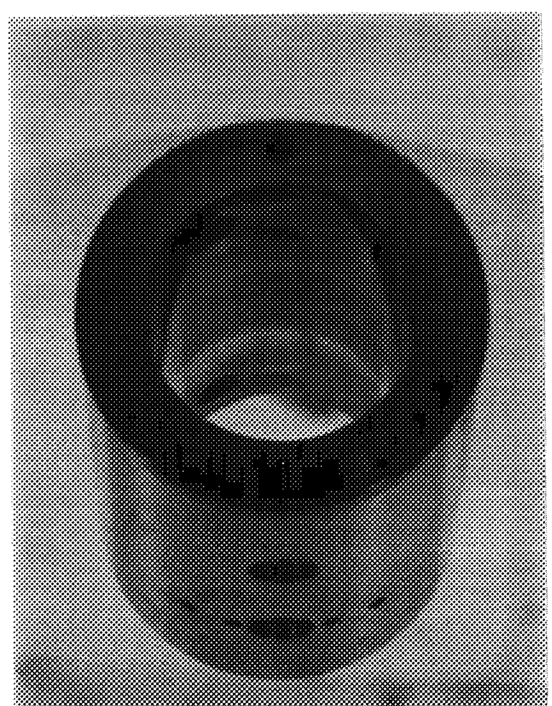
OIL FILTERS, TEST SHAFT, BEARING HOUSINGS, AND SHAFT LINER FROM TEST #4B USING HUMBLE FN-3158 PLUS 10% KENDALL RESIN

AFTER 100 HOURS AT 600°F



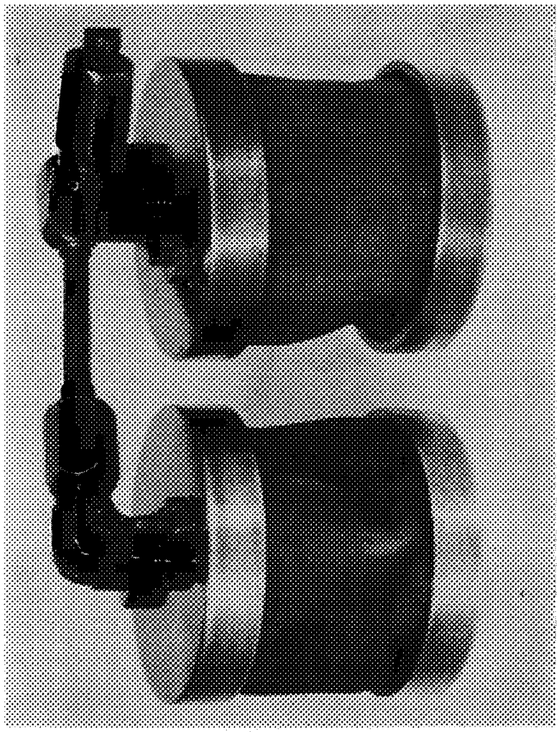


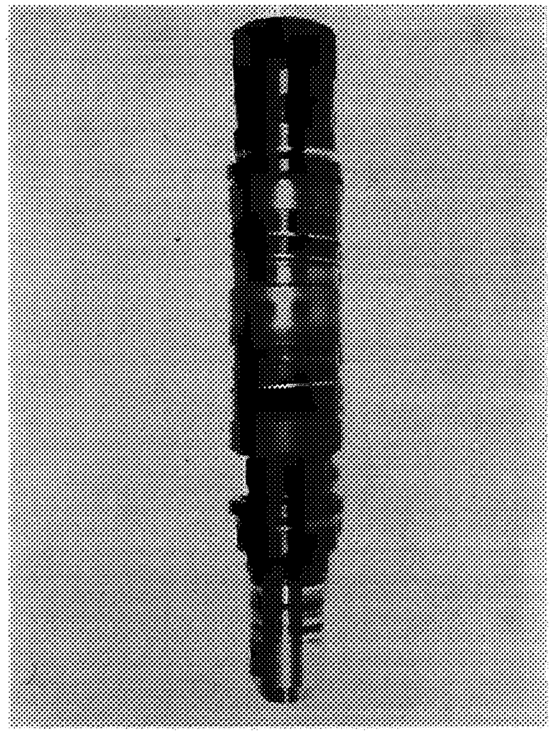


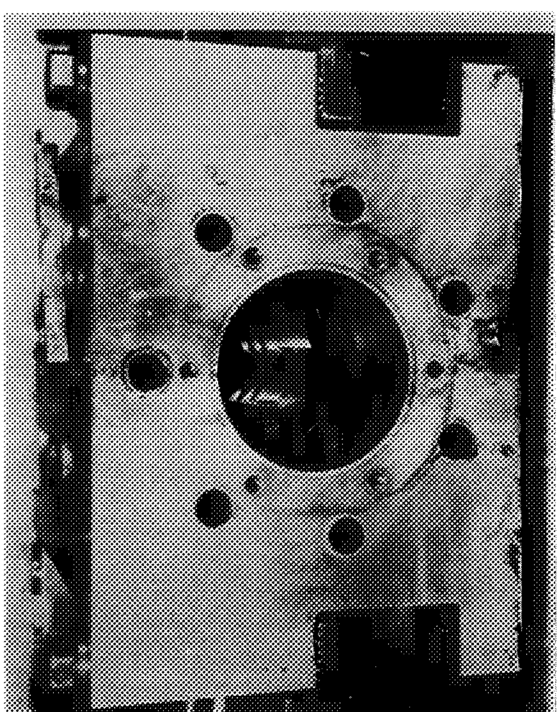


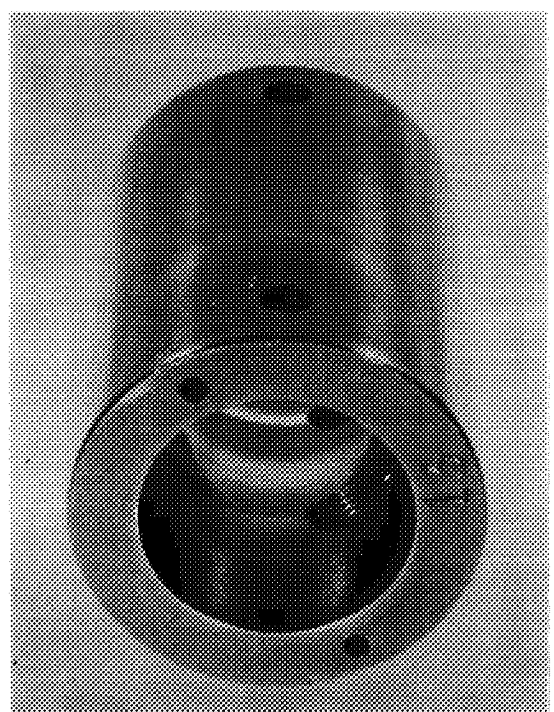
ENCLOSURE 53

OIL FILTERS, TEST SHAFT, BEARING HOUSINGS, AND SHAFT LINER FROM
TEST #5B USING DOW CORNING XF-1-0301
AFTER 100 HOURS AT 600°F



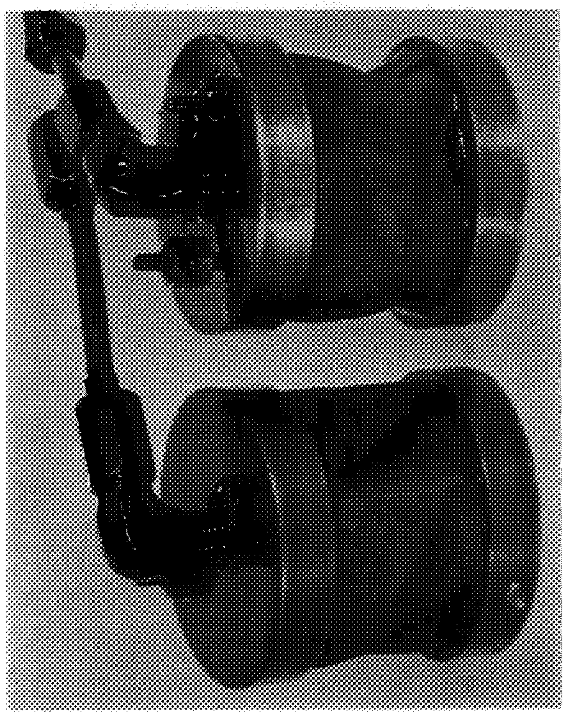


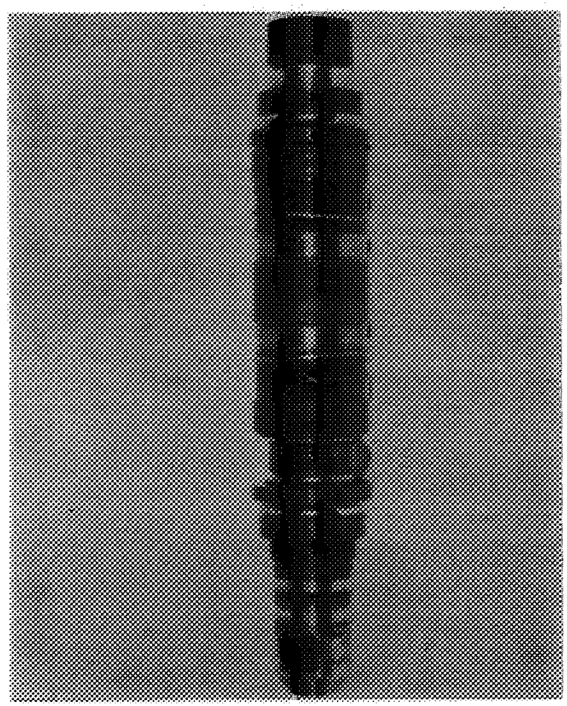


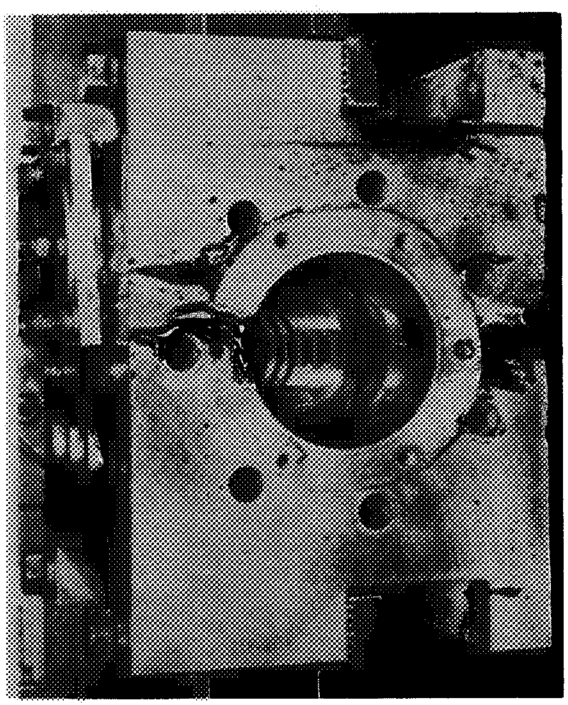


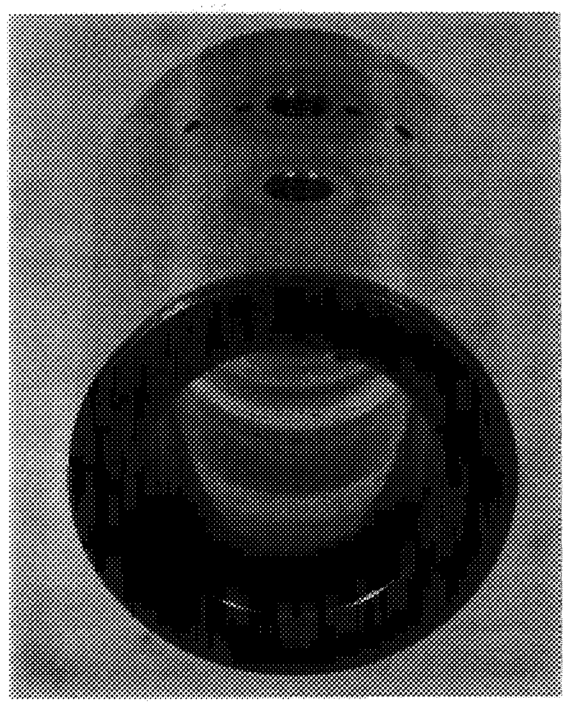
ENCLOSURE 54

OIL FILTERS, TEST SHAFT, BEARING HOUSINGS, AND SHAFT LINER FROM TEST #6B USING MOBIL XRM-109F PLUS 10% KENDALL RESIN AFTER 100 HOURS AT 600°F



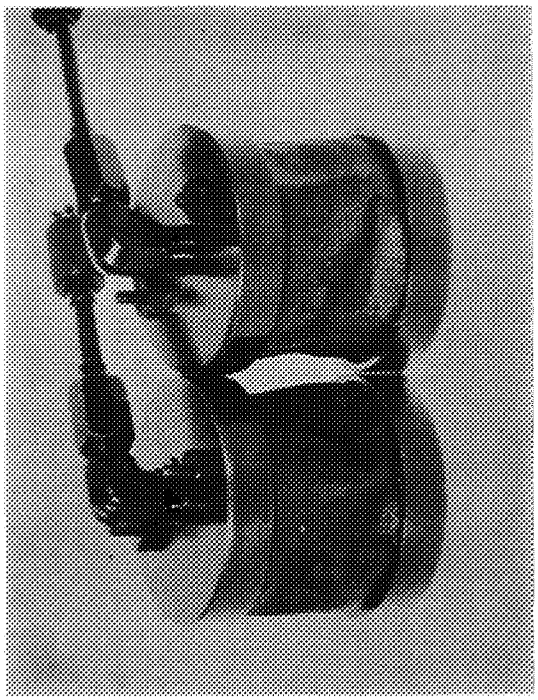


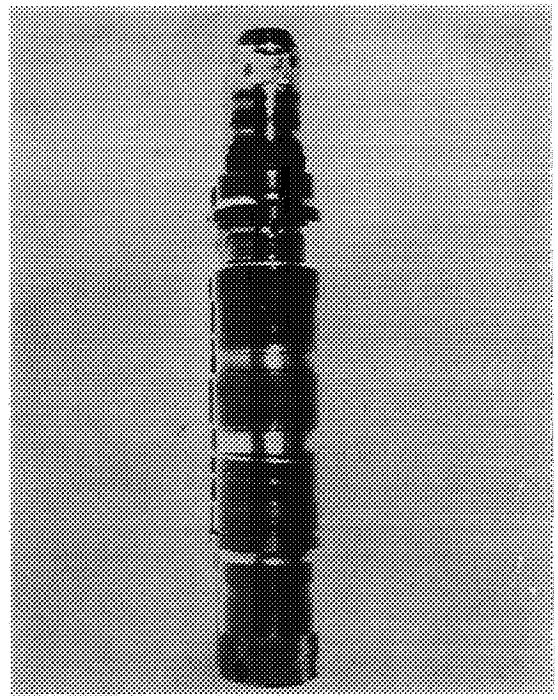


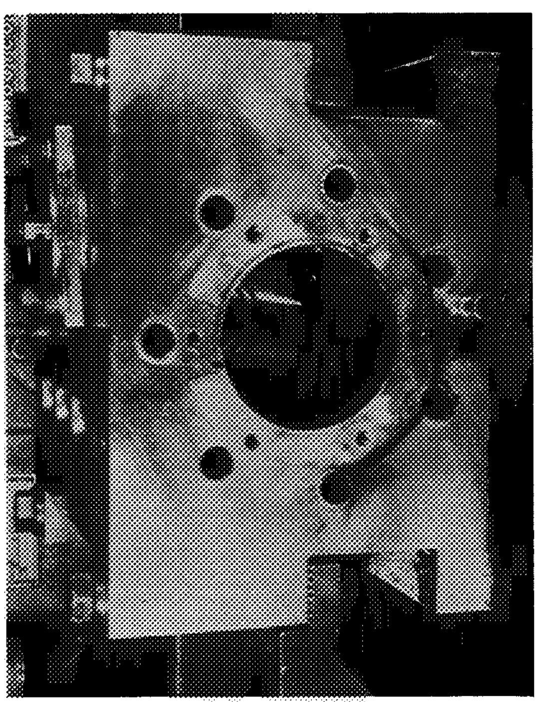


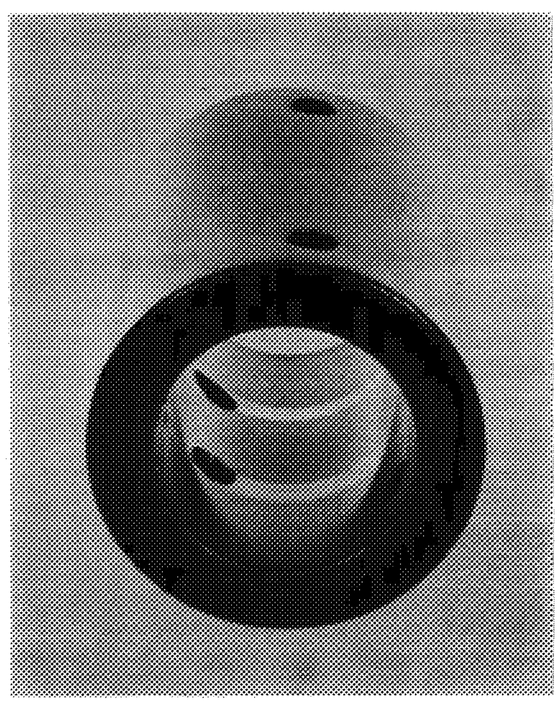
ENCLOSURE 55

OIL FILTERS, TEST SHAFT, BEARING HOUSINGS, AND SHAFT LINER FROM
TEST #7B USING ESSO AL07873
AFTER 100 HOURS AT 600°F









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81. Union Carbide Chemicals Co.
Research and Development Dept.
P.O. Box 65
Tarrytown, New York 10591 1

82. Sun Oil Company
Automotive Laboratory
Marcus Hook, Pennsylvania 19061
Attention: J. Q. Griffith 1

83. Mr. Martin Z. Zainman
Director of Research
Bray Oil Company
1925 N. Marianna Avenue
Los Angeles, California 80032 1

84. Sun Oil Company
Research and Development
Marcus Hook, Pennsylvania 19061
Attention: G. H. Hommer 1

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|---|---|---|
| 85. | Esso Research and Engineering Company<br>P.O. Box 8<br>Linden, New Jersey 07036<br>Attention: Mr. J. Moise | 1 |
| 86. | Eaton, Yale and Towne, Inc.<br>Research Center<br>26201 Northwestern Highway<br>Southfield, Michigan 48075<br>Attention: H. M. Reigner | 1 |
| 87. | United Aircraft Corporation<br>Pratt & Whitney Aircraft Division<br>Engineering Department<br>West Palm Beach, Florida 33402<br>Attention: R. E. Chowe | 1 |
| 88. | Shell Oil Company<br>Wood River Research Laboratory<br>Advanced Products Group<br>Wood River, Illinois<br>Attention: J. J. Heithaus | 1 |
| 89. | Grumman Aircraft Engineering Corp.<br>Bethpage, New York 11714<br>Attention: William Mayhew<br>M. Tarase | 1<br>1 |
| 90. | NASA-Lewis Research Center<br>Office of Assistant Director for Power<br>21000 Brookpark Road<br>Cleveland, Ohio 44135<br>Attention: Dr. B. Lubarsky, MS 3-3 | 1 |